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Methodology for the evaluation of Indoor Environmental Quality and Comfort in school classrooms through a multicriteria index

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To Elena, to the future

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Abstract

This dissertation develops an indicator that weighs the relevance of thermal, acoustic, light, and air quality parameters in evaluating indoor environmental quality (IEQ) in school classrooms. The study aims to determine the relationships between these parameters and students' perception of IEQ and design a methodology for weighting the parameters in a single index. It also aims to define the conditions under which students are forgiving of IEQ. The methodology used in this research is a mixed methodology that combines empirical, modelling, qualitative, and quantitative approaches.

The study begins by developing an IEQ index that combines thermal, acoustic, visual, and air quality parameters using secondary data from previous post-occupancy evaluations of classrooms in Chile. The index highlights the importance of noise, air quality, temperature, and light perception. However, a limitation of the index is the lack of data on general acceptability, which makes it challenging to compare the individual votes for each factor with the overall perception.

To address this limitation, a new survey is developed and validated specifically for school children aged 10 to 13 years. The survey assesses the acceptability of thermal, acoustic, visual, and air quality factors from the perspective of the students.

Based on the application of the survey a general comfort index was developed through multiple linear regression. Where AAV is Air acceptability vote, NAV is acoustic acceptability vote, LAV is Light acceptability vote and TAV is thermal acceptability vote.

$$I_{IEQ} = 0{,}47\mathrm{AAV} + 0{,}22\mathrm{NAV} + 0{,}16\mathrm{LAV} + 0{,}15\mathrm{TAV}$$

This index revealed that students prioritize air quality as the most important factor, followed by noise and temperature. Surprisingly, lighting has a negligible influence on their evaluation of IEQ. This contrasts with previous studies that emphasized thermal comfort as the primary factor. The research suggests that students' expectations and perceptions of IEQ can vary based on factors such as expectations. In this case, their understanding that to ensure good air quality during the COVID-19 pandemic, low temperatures inside the classroom were expectable.

To better understand the indoor conditions where students would evaluate their environment as acceptable, the measured parameters were correlated with the acceptability votes. It was found that the acceptability was not matching with normative requirements. Therefore, linear regressions and Binary logistic regressions were conducted to describe the conditions of acceptability.

The limitations of this study, include the small sample size and the constraints imposed by the COVID-19 pandemic, which affected occupancy density and ventilation rates. Future studies should address these limitations and explore the relationship between occupants' expectations and forgiveness regarding IEQ using the developed methodology.

In conclusion, this PhD research contributes to the evaluation of IEQ in school classrooms by developing an index and survey specifically for school children. The findings emphasize the importance of considering multiple aspects of IEQ, particularly air quality, in designing and renovating school buildings. It highlighted the need for further exploration of the relationships between different aspects of IEQ and occupants' expectations. This research demonstrates that occupants are forgiving of some aspects of IEQ if needed and hint at a relationship between expectations and forgiveness.

Keywords: multi-domain; combined effects; Indoor environmental quality; index; school classrooms

Resumen

Esta tesis doctoral propone un indicador que pondera la relevancia de los parámetros térmicos, acústicos, lumínicos y de calidad del aire en la evaluación de la calidad ambiental interior (IEQ) en aulas escolares. El estudio aspira a determinar las relaciones entre estos parámetros y la percepción de los estudiantes y diseñar una metodología para ponderar los parámetros en un índice único. También pretende definir las condiciones en las que los alumnos son indulgentes con la IEQ. La metodología utilizada en esta investigación es una metodología mixta que combina enfoques empíricos, de modelización, cualitativos y cuantitativos.

El estudio comienza con el desarrollo de un índice de IEQ que combina parámetros térmicos, acústicos, visuales y de calidad del aire basado en un conjunto de datos de evaluaciones post-ocupacionales de aulas en Chile. El índice destaca la importancia del ruido, la calidad del aire, la temperatura y la percepción de la luz. Sin embargo, una limitación del índice es la falta de datos sobre la aceptabilidad general, lo que dificulta la comparación de los votos individuales para cada factor con la percepción global. Para abordar esta limitación, se desarrolla y valida una nueva encuesta específica para escolares de 10 a 13 años. La encuesta evalúa la aceptabilidad de los factores térmicos, acústicos, visuales y de calidad del aire desde la perspectiva de los estudiantes.

A partir de la aplicación de la encuesta se elaboró un índice de confort mediante regresión lineal múltiple. Donde AAV es el voto de aceptación de la calidad del aire, NAV es el voto de aceptación de la calidad acústica, LAV es el voto de aceptación de la calidad lumínica y TAV es el voto de aceptación de la calidad térmica.

$$I_{IEQ} = 0{,}47\text{AAV} + 0{,}22\text{NAV} + 0{,}16\text{LAV} + 0{,}15\text{TAV}$$

Este índice reveló que los estudiantes dan prioridad a la calidad del aire como factor más importante, seguido del ruido y la temperatura. Sorprendentemente, la iluminación tiene una influencia insignificante en su evaluación de la IEQ. Esto contrasta con estudios anteriores que hacían hincapié en el confort térmico como factor principal. La investigación sugiere que las expectativas y percepciones de los estudiantes sobre IEQ pueden variar en función de factores como las expectativas.

Para comprender mejor las condiciones interiores en las que los estudiantes evaluarían su entorno como aceptable, los parámetros medidos se correlacionaron con los votos de aceptabilidad. Se comprobó que la aceptabilidad no coincidía con los requisitos normativos. Por lo tanto, se realizaron regresiones lineales y regresiones logísticas binarias para describir las condiciones de aceptabilidad.

Las limitaciones de este estudio incluyen el pequeño tamaño de la muestra y las restricciones impuestas por la pandemia COVID-19, que afectó a la densidad de ocupación y las tasas de ventilación. Futuros estudios deberían abordar estas limitaciones y explorar la relación entre las expectativas y la indulgencia de los ocupantes con respecto a la IEQ utilizando la metodología desarrollada.

En conclusión, esta investigación doctoral contribuye mediante el desarrollo de un índice y una encuesta específicos para escolares. Los resultados subrayan la importancia de considerar múltiples aspectos de la IEQ, en particular la calidad del aire, a la hora de diseñar y renovar edificios escolares. También se destaca la necesidad de seguir explorando las relaciones entre los distintos aspectos de la IEQ y las expectativas de los ocupantes. Esta investigación demuestra que los ocupantes son indulgentes con algunos aspectos de la IEQ si es necesario e insinúa una relación entre las expectativas y la indulgencia.

Palabras clave: multidominio; efectos combinados; calidad ambiental interior; índice; aulas escolares

Résumé

Cette étude doctorale développe un indicateur qui pondère la pertinence des paramètres thermiques, acoustiques, lumineux et de qualité de l'air dans l'évaluation de la qualité de l'environnement intérieur (QIE) dans les salles de classe écoliers. L'étude vise à déterminer les relations entre ces paramètres et la perception de la QIE par les élèves, et à concevoir une méthodologie pour pondérer les paramètres dans un indice unique. Elle vise également à définir les conditions dans lesquelles les élèves sont indulgents à l'égard de la QIE. La méthodologie utilisée dans cette recherche est une méthodologie mixte qui combine des approches empiriques, de modélisation, qualitatives et quantitatives.

L'étude commence par l'élaboration d'un indice de QEI qui combine des paramètres thermiques, acoustiques, visuels et de qualité de l'air, sur la base d'un ensemble de données provenant d'évaluations antérieures d'occupation de salles de classe au Chili. L'indice souligne l'importance du bruit, de la qualité de l'air, de la température et de la perception de la lumière. Cependant, l'une des limites de l'indice est le manque de données sur l'acceptabilité générale, ce qui rend difficile la comparaison des votes individuels pour chaque facteur avec la perception globale.

Pour remédier à cette limitation, une nouvelle enquête a été élaborée et validée spécifiquement pour les écoliers âgés de 10 à 13 ans. L'enquête évalue l'acceptabilité des facteurs thermiques, acoustiques, visuels et de qualité de l'air du point de vue des élèves.

Sur la base de l'application de l'enquête, un indice général de confort a été développé par régression linéaire multiple. Où AAV est le vote d'acceptation pour la qualité de l'air, NAV est le vote d'acceptation pour la qualité acoustique, LAV est le vote d'acceptation pour la qualité de l'éclairage et TAV est le vote d'acceptation pour la qualité thermique.

$$I_{IEQ} = 0{,}47\text{AAV} + 0{,}22\text{NAV} + 0{,}16\text{LAV} + 0{,}15\text{TAV}$$

Cet indice révèle que les étudiants considèrent la qualité de l'air comme le facteur le plus important, suivi du bruit et de la température. Il est surprenant de constater que l'éclairage n'a qu'une influence négligeable sur leur évaluation de la qualité de l'environnement intérieur. Cela contraste avec les études précédentes qui mettaient l'accent sur le confort thermique en tant que facteur principal. La recherche suggère que les attentes et les perceptions des étudiants en matière de QIE peuvent varier en fonction de facteurs tels que les attentes.

Pour mieux comprendre les conditions intérieures dans lesquelles les étudiants évalueraient leur environnement comme acceptable, les paramètres mesurés ont été corrélés avec les votes d'acceptabilité. Il a été constaté que l'acceptabilité ne correspondait pas aux exigences normatives. Par conséquent, des régressions linéaires et des régressions logistiques binaires ont été effectuées pour décrire les conditions d'acceptabilité.

Les limites de cette étude comprennent la petite taille de l'échantillon et les contraintes imposées par la pandémie de COVID-19, qui a affecté la densité d'occupation et les taux de ventilation. Les études futures devraient tenir compte de ces limites et explorer la relation entre les attentes des occupants et leur tolérance à l'égard de la QEI en utilisant la méthodologie développée.

En conclusion, cette recherche doctorale contribue à l'évaluation de la QIE dans les salles de classe en développant un indice et une enquête spécifiques pour les écoliers. Les résultats soulignent l'importance de prendre en compte les multiples aspects de la QIE, en particulier la qualité de l'air, lors de la conception et de la rénovation des bâtiments scolaires. Ils soulignent également la nécessité d'explorer davantage les relations entre les différents aspects de la QEI et les attentes des occupants. Cette recherche démontre que les occupants sont indulgents à l'égard de certains aspects de la QEI si nécessaire et laisse entrevoir une relation entre les attentes et l'indulgence.

Mots-clés : multi-domaines ; effets combinés ; qualité de l'environnement intérieur ; indice; classes d'école

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Glossary

A

Adaptation, Thermal: Adjustment made by the building occupants to avoid or limit thermal discomfort. It can be a physiological, psychological or behavioural change.

Adaptation, perceived air quality: Adjustment of the senses to perceived odour (air quality), which occurs during the first 15 minutes of exposure to bio effluents.

Airing: Increasing the ventilation of a room by deliberately opening windows, doors, vents, etc.

Airspeed: The velocity of air movement at a given point in time regardless of the direction.

Alliesthesia: Term defined by Cabanac (Cabanac, 1971) “a given external stimulus can be perceived either as pleasant or unpleasant depending upon signals coming from inside the body”

Analytic Hierarchy Process (AHP): Is a structured technique for evaluating complex decisions in a group decision-making. This technique is used in scenarios where the complexity of the problem makes the decision unclear. AHP decomposes the problem into a hierarchy of more easily comprehended sub-problems, to be then analysed independently by a group of experts.

Attention Restoration Theory: The idea that natural environments provide a restorative reprieve from cognitive demands by engaging the mind passively through fascination to relieve attention fatigue. Through design elements that inspire fascination, we can bring meaningful richness and sensory experience into the learning environment.

B

Background Noise Level (L_{eqAS}): the steady sound pressure level which, over a given period of time, has the same total energy as the actual fluctuating noise

Binary Logistic Regression: This technique can be applied when the dependent variable is categorical or has been turned into a categorical dichotomous[1] variable, where both categories are mutually excluded. When using this technique, it is possible to evaluate the impact of multiple independent variables that are present simultaneously on the dependent variable.

C

Clo: Unit of measurement that characterizes the thermal insulation from clothing. This notion is used to calculate PMV and to evaluate the adaptative strategies used by the occupants to acclimate to the indoor thermal environment.

Cross-modal perception: Cross-modal perception occurs when two or more senses interact with each other.

D

Data: Data are pieces of information that are collected or analysed through a study. Most data can be classified as numerical or categorical. Numerical data can be discrete or continuous and the statistical analyses applicable to each dataset will vary based on this categorization.

Numerical data: they have meaning as a measurement, therefore they are quantitative data. Numerical data can be further broken into two types: discrete and continuous.

Discrete data: represent items that can be counted. If the possible values are fixed (finite), it mean that there is a limit to the possible values that can be listed out.

Continuous data: their possible values cannot be counted and can only be described using intervals on the real number line.

[1] 2 categories

Categorical data: Represent characteristics such as a person's gender, marital status, etc. Categorical data can take on numerical values (such as "1" indicating male and "2" indicating female), but those numbers don't have meaning.

E

Expectation, Environmental: the hopes or beliefs that the indoor environmental quality of an indoor space will concide with the conditions that the occupant wants. The conditions wanted by the occupant could be defined by several factors including previous experiences.

F

Forgiveness factor: Is a ratio of Overall Comfort score to the average of the scores for the six environmental factors: Lighting Overall, Noise Overall, Temperature Overall in both winter and summer, and Air Overall in both winter and summer in the BUS survey (Leaman and Bordass 2007). This index intents to quantify the user's tolerance of the environmental conditions in the building.

I

Indoor environmental quality (IEQ): A perceived indoor experience of the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings. Fields of specialization include architecture, HVAC design, thermal comfort, indoor air quality (IAQ), lighting, acoustics, and control systems (ASHRAE Terminology)

Indoor environmental expectation (IEE): People have different expectations of what a comfortable indoor environment should be. These expectations vary depending previous experiences, and can be related to cultural aspects.

M

Multivariate Logistic Model: This type of model is used to predict the relationships between dependent and independent variables by calculating the probability of something happening depending on multiple sets of variables. This is a common classification algorithm used in data science and machine learning.

Multiple Linear Regression (MLR): This model describes how a dependent variable, in this case, comfort, depends linearly on several predictor variables.

Multiple Non–Linear Regression: This model describes how a dependent variable, depends non-linearly on several predictor variables. Observational data are modelled by a function which is a nonlinear combination of the model parameters. The data are fitted by a method of successive approximations, and the curve can take almost any form.

N

Non–Parametric Spearman Correlation Analysis (NPSCA): This technique organized variables into ranks and then looks at the correlation between two sets of ranks. This means that the correlation coefficient uses only the ranks of the values and not the values themselves. Through this transformation, we can evaluate and compare ordinal and continuous variables. For the interpretation of this correlation, it is relevant to note that the resulting values will lie between -1 and +1. When the observations are given exactly the same rank, then the resulting value will be 1, if they are assigned exactly the opposite rank, the resulting value will be -1. In both cases, we will see a strong correlation, in the first case a positive and in the second case a negative correlation. When the resulting coefficient approaches 0, it indicates that there is no found correlation. Even if the correlation coefficient is zero, a non-linear relationship might exist.

P

Predicted Mean Vote (PMV): Based on the heat balance of the body, this index predicts the mean value of votes of a group of occupants on a seven-point thermal sensation scale. Different methods can be used to assess this for different combinations of metabolic rate, insulation, temperature, airspeed, mean radiant temperature, and relative humidity. This index was developed for healthy middle aged adults.

Predicted Percentage of Dissatisfied (PPD): This index predicts the percentage of thermally dissatisfied occupants (i.e., too warm or too cold), and is calculated from the PMV

Prevailing mean outdoor temperature ($\boldsymbol{\theta}$rm): Is the arithmetic average of the mean daily outdoor temperatures over no fewer than 7 and no more than 30 sequential days prior to the day in question (ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy).

Pearson Correlation Analysis: This coefficient will only reflect linear correlations and can only be applied to "either two continuous or two ordinal variables or a combination of an ordinal and a continuous variable, but not for two nominal variables" (Heumann et al., 2016, Chapter 4.3.3). Pearson's coefficient uses the entire information contained in the continuous data.

Proportional Ordinal Logistic Regression: Proportional odds logistic regression can be applied when there are more than two outcome categories that have an order, either discrete or continuous. An important underlying assumption is that no input variable has a disproportionate effect on a specific level of the outcome variable.

R

Reverberation Time (RT): Is the time (in seconds) it takes for the sound from a source to decrease in level by 60 dB after the source has stopped.

S

Speech Transmission Index (STI): This index gives a numerical value to speech transmission quality, and can assume values between 0 and 1, were 1 means that a speech has absolutely perfect intelligibility (which is virtually impossible). Terefore, the lower the STI, the more degraded the quality of speech intelligibility becomes.

Signal-to-Noise Ratio (SNR): Is a measure that compares the level of a desired signal to the level of background noise.

T

Temperature, Operative (Top): Is a measure that combines the air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two, were the weight depends on the heat transfer coefficients by convection (hc) and by radiation (hr) at the clothed surface of the occupant (Nicol et al., 2012).

Thermal comfort: Is the condition of mind that expresses satisfaction with the thermal environment as measured through a subjective evaluation. (ASHRAE 55, 2017)

Thermal sensation: Assesment to determine whether a specific thermal condition can be considered comfortable or not. There are several scales to evaluate thermal sensation.

Thermal Neutrality:The indoor thermal index value corresponding with a neutral PMV on the thermal sensation scale.

V

Variable : A variable is any characteristic or numerical value that varies from individual to individual. A variable can represent a count (for example, the number of pets you own); or a measurement (the time it takes you to wake up in the morning). Or the variable can be categorical, where each individual is placed into a group (or category) based on certain criteria (for example, political affiliation, race, or marital status). Actual pieces of information recorded on individuals regarding a variable are the data.

1 Introduction

This chapter presents the general context of this PhD dissertation and describes the topic and context of the study. It summarizes the focus and scope of the research as well as the relevance of the study in its context and as original research.

Afterwards, the questions, objectives and general hypothesis defined for this research are presented. Finally, the general structure of the document is described.

1.1 Problem statement

The quality of the built environment can be studied from different perspectives. And it has been so during the evolution of the field. One approach to the problem is architectural science, positioned closer to engineering, which seeks to simplify the complex issue of perception of the indoor environment by developing standards, and evaluation tools among others. Other authors Indoor environmental quality (IEQ) is a broad concept, which seeks to define when a built space, provides welfare to its occupants. In general, it is defined as the condition of thermal, visual, acoustic and air quality comfort and depends on multiple factors, which can be classified into four categories; conditions of the external climate, spatial configuration and the envelope of the building, facilities and activities and factors of use (Almeida et al., 2015). ASHRAE defines this concept as “a perceived indoor experience of the building indoor environment that includes aspects of design, analysis, and operation of energy-efficient, healthy, and comfortable buildings”(ASHRAE, 2023) that is determined by design decisions made by specialists on the areas of architecture, HVAC design, thermal comfort, indoor air quality (IAQ), lighting, acoustics, and control systems.

The importance of the quality of the interior environment is related to its effects on the well-being and health of the people who use the interior spaces, understanding that the lack of environmental comfort, has negative effects on the health of people and on the performance of the occupants. Some of these negative effects are known as the sick building syndrome, originally described by Burge and others (1987) which refers to the relationship of symptoms such as lethargy, dry nose, dry throat, and headache, with problems of ventilation, contamination, and humidification of the air. Other negative effects are the lack of concentration either by very low or very high temperatures, the sensation of suffocation when the relative humidity of the air is too high, headaches or difficulty focusing product of loud or constant noise, the sensation of tired eyes and glare, by inadequate lighting levels, among others.

In Chile, there is a struggle caused by the low indoor environmental quality of educational spaces and its negative effects on students’ welfare and learning outcomes. It is public knowledge that the existing educational buildings in Chile do not have adequate heating systems or provide comfortable temperatures for students and teachers, which is reflected in the news published during the winter of 2018 about the low temperatures inside classrooms. (Almazabar, 2018; Gonzalez & Nuñez, 2018; Hillmann & Muñoz, 2018). On the other hand, the acoustic, lighting and air quality conditions are presumed to be deficient, since the current regulatory framework does not consider those aspects (Decreto 548, 2012) or proposes insufficient compliance values. It is relevant to consider that Chilean students are those who spend more time at school compared to other OECD countries (OECD, 2018), with a stay in the classroom between 30 and 42 hours per week depending on the level and schedule (Ministerio de Educación, 2018).

To define a comfortable space, it is necessary to state a methodology to assess the environmental quality (IEQ) for students and teachers in school classrooms, considering the four aspects that define IEQ: Thermal comfort, Indoor air quality, visual comfort, acoustic comfort in an integrated manner and to define verifiable standards, consider the time of exposure and thus ensure an educational space that delivers environmental comfort to its occupants.

Research on environmental quality (IEQ) in schools generally refers to one or two aspects of the four, even the most recent research deals with these topics separately, such as the post-occupational assessment of thermal comfort and its congruence with the existing thermal comfort models (Martinez-Molina et al., 2017; Trebilcock et al., 2017a), thermal comfort and air quality, air quality and acoustics, without consider all the factors that influence the environmental quality of the spaces with a systemic approach.

It is understandable that the reductionism generated by isolating parameters (thermal, acoustic, air quality, lighting) allows us to study a parameter in detail but does not provide an evaluation of the environmental quality of the space. That is why a metric is necessary to integrate the factors that influence environmental quality with a comprehensive and holistic approach, that allows to evaluate and compare educational spaces, understanding that the perception of comfort of people depends on multiple factors that simultaneously occur in a space.

1.1.1 Indoor environmental quality in schools in Chile

In Chile, public education is governed by different regulations and decrees that define the minimum quality requirements. Currently, these are very basic or non-existent as is the case of respiratory and acoustic comfort in school classrooms, as presented in **Table 1.1**. The current requirements for minimum temperatures are not concurrent with comfort temperatures and apply only to some areas and considering the climatic diversity of Chile, it would be advisable to also include a maximum temperature limit inside the classrooms.

Levels of artificial lighting are very low, especially for classrooms (150lux). This situation is intended to be solved with a regulatory proposal developed by CITEC UBB for the Ministry of Education in 2018 (unpublished) that seeks to establish environmental comfort requirements in line with the current situation of the country and international experience.

In this framework of regulatory deficiencies, research has been related to thermal comfort in school classrooms such as the one directed by Trebilcock (2017a), where thermal comfort was evaluated in schools in different climatic zones of Chile.

It is important to highlight the efforts made by the Ministry of Education to improve environmental quality and education in public schools. Among the measures taken, budgets were increased for the design and construction of new schools, which must have energy efficiency studies and comply with the design recommendations, included in the ministry's publications such as the Design Criteria for the new ones. Educational spaces (Departamento de Infraestructura Escolar del Ministerio de Educación, 2015). These criteria have been applied voluntarily in the “Sello” schools of the Ministry of Education.

To evaluate the use and comfort of school spaces in educational establishments built or restored between 2010 and 2015, the "School infrastructure and learning study" project commissioned by the IDB and the Ministry of Education to Idiem of the Catholic University of Chile was carried out. In this study, specific measurements were taken of lighting conditions (natural and artificial), acoustics, temperature and indoor air quality in 21 educational establishments in different communes and climatic conditions. (Idiem 2017).

Table 1.1: *environmental quality requirements for schools in Chile*

Parameter	*Norm/decree*	*requirement*	*threshold*
Temperature	Decreto 548, Artículo 9.7	Minimum temperature for nurseries[2]	15 °C
		Temperature minimum 7 to 18 years[3]	12 °C
Illuminance	Decreto 548, Artículo 9.6	Illuminance minimum, artificial lightning	300 lux circulations 150 lux minimum for class area
Air Quality	--	--	--
Noise mitigation	--	--	--

The results of the evaluation are generally positive regarding indoor temperatures, where between 62% and 40% of the establishments present comfortable temperatures, for a day of summer or spring. In lighting, only 7.1% of the classrooms meet the requirement of 300 lux, although all of them have a good or acceptable uniformity. Noise measurements were made in the exterior spaces of the establishment, so they are not considered. In the case of air quality, 76.2% of schools fall within category 2 (400 to 600 ppm of CO_2 over outdoor air), which is recommended by UNE 13779/2008. How the results of this study only refer to indoor environmental quality for a day in spring/summer in each establishment. Therefore, they do not reflect the conditions throughout the year.

It can be concluded that there is an interest in improving environmental quality within educational establishments and that the Ministry of Education has invested in the evaluation of performance and the renewal of regulations to ensure environmental quality in schools in the country. Given the available information, it is not possible to conclude about the quality of the indoor environment, since the measurements do not consider all the factors and parameters necessary to evaluate the interior quality, at the same time there is no information on the perception of environmental comfort on the part of the students.

[2] Only applicable for the Andean region, central middle region, south of Maipo river, costal south, interior south and extreme south.

[3] Only applicable for the Andean region, central middle region south of Ñuble and Itata rivers, costal south, interior south and extreme south.

1.1.2 IEQ in school buildings

Indoor Environmental Quality (IEQ) is composed of four separate but interrelated elements: thermal comfort, respiratory comfort or air quality, visual comfort and acoustic comfort and the difficulty in evaluating each one of them and, lies in that they are subjective opinions about the quality of a space. When trying to combine the different aspects, this difficulty materializes, as Humphreys (2005) explains: if a user qualifies a building as "bad" acoustically, but "good" in lighting, it will depend on the relative importance that the user gives (based on to the task you are doing, your experience, among others) to both factors your evaluation of the interior environmental comfort. His research suggests that people do not negatively evaluate the space based on a deficiency, but that in general, they are more indulgent.

In the same publication, which is based on the results of surveys conducted in 26 offices in Europe within the framework of the SCATs project, Humphreys concludes that it is not possible to develop environmental comfort indexes that are internationally valid and therefore it is better to continue with unitary analyses, although a more positive view will suppose that indexes referring to a specific activity can be developed, which would be equally useful for the design and decision making, although with local application.

Huang and others (2012) recognize the difficulty to assess the multiplicity of factors that influence the perception of the environmental quality of people since there are complex relationships between different climatic, spatial, and psychological factors, from which it can be deduced that this opens a field of research that is currently under development. Kim and De Dear (2012), for their part, state that currently there is no consensus regarding the relevance of the different factors of indoor environmental quality (IEQ) on the perception of comfort of people.

Regarding the relevance of the different factors, the study carried out by Barrett and others (2015) on schools and classrooms is interesting, where they state that in the case of school classrooms in England, the most influential aspects on the performance of students are lighting, temperature and air quality (49%) while spatial aspects such as colour, complexity, appropriateness and flexibility explain the rest (51%). Barrett also mentions that the results presented are valid in the context of the study and are not significant outside of England.

The Heschong Mahone Group studied the impact of lighting and other IEQ aspects on learning in schools in the Fresno Unified School District, located in California’s Central Valley. This research used statistical analysis controlled for other aspects such as demographics and teachers’ characteristics to better understand the correlations between IEQ and productivity. The main findings are summarized in **Table 1.2.**

Table 1.2: *Summary of findings by Mahone and Oaks.* (2003, p. ix)

Relevance of visual environment for learning

- An ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, supports better outcomes of student learning.
- Sources of glare negatively impact student learning. This is especially true for math learning, where instruction is often visually demonstrated on the front teaching wall. Per our observations, when teachers have white marker boards, rather than black or green chalkboards, they are more likely to use them and children perform better in math.
- Direct sun penetration into classrooms, especially through unshaded east or south-facing windows, is associated with negative student performance, likely causing both glare and thermal discomfort.
- Blinds or curtains allow teachers to control the intermittent sources of glare or visual distraction through their windows. When teachers do not have control of their windows, student performance is negatively affected.

Relevance of acoustic environment for learning

- Situations that compromise student focus on the lessons at hand, such as reverberant spaces; annoying equipment sounds, or excessive noise from outside the classroom, have measurable negative effects on learning rates.

Relevance of ventilation and air quality for learning

- Poor ventilation and indoor air quality also appear to negatively affect student performance. However, in FUSD these issues are almost hopelessly intertwined with thermal comfort, outdoor air quality and acoustic conditions. Teachers often must choose to improve one while making another aspect of the classroom worse.

Relevance of Physical Characteristics of classrooms for Learning

- Physical characteristics of classrooms are just as likely to affect student learning as many other factors commonly given much more public policy attention. Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance.

Methodologies and indicators used in the evaluation of IEQ in classrooms

At the international level, there is no consensus on the methods, indicators, and equipment to be used for the evaluation of the internal environmental quality (IEQ) (Heinzerling et al., 2013a), the reviewed studies can be classified grosso modo in qualitative, short period quantitative and longer period quantitative studies. Research on school buildings focuses on the classroom unit and evaluates different parameters as shown in Table 1.3.

Bluyssen, Zang, Kurvers and others (2018) evaluated comfort and health levels in school classrooms using data collection tools adapted and based on SINPHONIE (Csobod 2010) and Giuli (2010) and measurements every 15 seconds by 30 as data collection tools. minutes during the survey application. The respondents were children between 9 and 11 years old and the survey was conducted on paper with the supervision of a researcher, which achieved 87% of responses, a response rate considered very good. On the other hand, the monitoring of environmental parameters was considered very short. The results showed that noise is the main complaint among students, another interesting result is that all environmental parameters were evaluated better in alternative schools (Waldorf, etc.) than in traditional schools. One could propose a relationship between the incorporation of dynamic teaching-learning methodologies and the consequent adaptation of classroom use, and greater control and autonomy on the part of students, who could manipulate elements such as windows, move within the classroom or modify the type of clothing, without affecting the development of the class which would improve your perception of comfort by having a greater ability to adapt.

Barrett et al. (2009), in the HEAD project (Holistic Evidence and Design) seek to expand the study of interior environmental quality (IEQ) from the aspects of temperature, lighting, acoustics and air quality to a holistic vision that includes aspects of "spatial quality" in educational spaces in England. The methodology used is mixed, with surveys and semi-structured interviews with teachers and a photographic survey and description of the space in 153 classrooms in 27 schools. For the spatial definition, researchers define 30 factors to study based on 18 indicators divided into three design principles (Table 4). The data collected were contrasted with the results of the students' school performance through a multi-level statistical model (MLM) to find correlations between the spatial and comfort qualities of the classrooms and the performance of the students.

The main results presented are that "... the physical characteristics of the primary schools impact the progress in reading, writing and mathematics". This impact is quite high, explaining 16% of the variation in the overall progress during a year of the 3766 students who participated in the study. Note that the parameters of acoustics, relationship with nature and spatial connectivity do not appear as relevant after the analysis with the multi-level statistical model (MLM) (Barrett et al., 2013)

It is noteworthy that this study allows us to expand the spectrum of factors that influence school performance beyond studies that have focused only on indoor environmental comfort (IAQ). Another relevant factor that appears because of this research is that, in the case of elementary students, the classroom is very relevant in performance, with no direct relationship between the spatial quality of the whole school and performance.

In general, this study envisages a relationship between spatial quality, viewed from a holistic perspective and school performance. It is important to point out that the results of this study cannot be extrapolated to other realities, since the relevance of the factors should be related to aspects of infrastructure quality, culture and permanence in space, among others.

Table 1.3: *Overview of studies of IEQ in classrooms*

Study/protocol	*Acoustics*	*IAQ*	*Lightning*	*Temperature*	*Comfort*
Bluyssen et al. (2018) 30 min., intervals of 15 sec. (37 classrooms)	--	CO_2	--	Temperature Relative humidity	Children's Building Symptom index Children's Personal Symptom index Children's Building comfort index
Sadick, Issa (2017) 32 schools	Background noise dB(A) Reverberation time (RT60 at 1KHz)	CO_2	Daylight factor	Temperature Relative humidity	1. Semi-structured interviews with teachers 2. online survey and sample measurements
Toyinbo et al. (2016) Several weeks of summer (108 classrooms)	--	CO_2	--	Temperature Flow	Questioners to principals of the schools and students
De Giuli et al. (2012) 28 classrooms	--	CO_2	Emin (lux) Emax (lux) On/off Shadings up/down	Air Temperature Relative humidity Globe temperature	51 questions questionnaire
Barrett, Zhang, Davies, Barrett (2015) Spot measurements 27 school	Noise levels	CO_2	Illumination levels	Air Temperature Relative humidity	Architectural measurements questionnaire-based interview

1.1.3 Forgiveness factor

A key concept that will be challenged in this research is the Forgiveness factor[4], as it was defined by Leaman and Bordass (2007) in the framework of the Building Use Studies (BUS) project in England. This concept refers to the ability of users to extend their comfort zone, overlooking problems with their thermal environment (Leaman Thomas Vandenberg 2007). In the publication by Leaman and Bordass (2007, p.664), 'Forgiveness' is defined as "dividing individual building mean scores for the variable comfort overall by the average of scores for the variables temperature in summer overall, temperature in winter overall, ventilation/air in summer overall, ventilation/air in winter overall, lighting overall, and noise overall", which shows that the concept is equally applicable to Environmental Comfort, although the equation does not consider the weighting of different aspects. This concept seems adequate to define the Forgiveness or indulgence of the students concerning the parameters measured through a post-occupational evaluation of the classrooms. This concept has not been further developed in other publications but presents a positive view of how people will react to the conditions of their environment. For the case of schools, it seems reasonable to ask for the users to tolerate episodes of discomfort, if it does not affect their health and wellbeing.

1.2 Research questions and hypothesis

General hypothesis

Students will be forgiving with certain aspects of IEQ while other thresholds are met.

4 Forgiveness is a derived score obtained by dividing the score for the summary variable "comfort overall" by the average of the summary variables for temperature in summer and winter, ventilation/air in summer and winter, noise and lighting.

1.3 Aim and objectives

This PhD aims to develop an indicator that will allow **weighting of the relevance of the four aspects of IEQ**, with respect to the general comfort of students in school classrooms, allowing the evaluation and comparison of the quality of the spaces. The following working objectives are defined to prove the **hypothesis** that **students will be more indulgent (or forgiving) with certain aspects of IEQ while other thresholds are met.**

1. Determine the relationships between the thermal, acoustic, light and air quality parameters and requirements and the IEQ for students within the classrooms and delineate an index.
2. Evaluate the environmental conditions and the perception of the environmental comfort of the students in educational establishments to weigh the relevance of each parameter on the index.
3. Develop a tool to gather the necessary data to describe IEQ in a weighted index.
4. Design a methodology that allows weighting in a single index the environmental factors to predict environmental comfort.
5. Define the indoor environmental conditions under which students will be forgiving of the IEQ.

The relationship between each objective, the general methodology and the chapters in this document is described in **Figure 1.1**.

1.4 Significance

This research is aligned with the emerging research area of IEQ evaluation and assessment of educational spaces, which has been gaining attention since 2010. This field is being developed where some research groups in Europe (Bluyssen in Delft, Buratti at Università degli Studi di Perugia) have been looking into relations between comfort perception and IEQ, health and wellbeing. The originality is in the hypothesis that states that "students will be more indulgent (or forgiving) with certain aspects of IEQ while other thresholds are met" including the concept of «forgiveness » coined by Leaman and Bordass in 2007 but adapting it to reflect the different weight that the users (in this case school students) give to each of the aspects of IEQ.

The methodological approach, mixed method, is innovative in this field as it combines empirical, modelling, qualitative and quantitative research, in a sequential exploratory approach. The validated survey for the evaluation of Forgiveness and IEQ in schools will set a precedent in this type of study, as no other survey has been developed with this objective and for this specific typology of buildings.

The resulting Index, and the statistical analysis made to develop it, will contribute to the current discussion on the development of indicators for IEQ.

Since the case studies and validation will be carried out in Chile, the developed index will only be applicable in that context. Nevertheless, the methodology developed to define the weighting of each factor should be applicable in other contexts. It is expected that changing the climatic and sociocultural context will affect the weight given to each aspect of IEQ in the index.

1.5 Research boundaries

Multicriteria analysis of the indoor environment is a novel and rapidly developing topic of research. This dissertation is focused on the evaluation of IEQ in school classrooms in Chile while proposing a methodology that would be applicable in other contexts. This dissertation is positioned in this area of research, maintaining the following boundaries:

- For this research IEQ includes indoor air as well as visual, thermal, and acoustic parameters. Psychosocial and special aspects are out of scope at this stage.
- This research is focusing on IEQ in school classrooms, other spaces within schools are not studied.
- Since the study is done on existing classrooms, they are traditional classrooms designed according to the regulations with the teacher at the centre of interaction, and located near the main wall that also has the whiteboard.
- Although the terms well-being and health are mentioned in this research, they are not part of the aim and objectives, and will not be contrasted with the results of the research.

Chile has been defined as a natural laboratory for climate change, due to its climate diversity. For the evaluation of IEQ, the variability of climates in the country as well as the availability of equipment and established researchers on thermal comfort and sustainability in the indoor environment, present the opportunity to understand the problem of IEQ in school classrooms in different contexts. At the same time, the result of the study would be useful for the design and construction of new schools as well as the renovation of existing ones. Chile is planning to evaluate the current state of the over 7.000 public school buildings during 2023 to evaluate possible retrofitting (MINEDUC, 2022). Therefore, the study could inform the retrofitting strategies.

1.6 Thesis structure

Chapter 2 presents the state-of-the-art and theoretical framework for the study of IEQ in classrooms. It defines each of the four main aspects of indoor environmental quality, then presents the measuring techniques used to evaluate each of them, threshold, and normative requirements. Then, the relevance of the context and other factors are reviewed. At last, the research gap is identified.

Chapter 3 develops the research methods used in this PhD study. It first presents the contextual limitations, then the research design is described. Including sample selection for all case studies, including the Socio-Environmental context of the study and the characteristics of the climate, data management and the statistical methods used.

Chapter 4 presents an exploration of the effects that environmental factors, as well as climatic conditions and seasons, have on the concentration of CO_2 in school classrooms. The main results of this research show that season has an impact on thermal and air quality environment. In winter, the need to conserve heat diminishes ventilation, promoting CO_2 concentration build-up, while in spring the adaptative response is to open windows to lower the temperature, this strategy also lowers CO_2 concentration. Finally, it was found that indoor temperature is a relevant factor in predicting CO_2 concentrations.

Chapter 5 presents a methodological approach to the development of an index that summarizes the evaluation of Indoor Environmental Quality (IEQ) from the perspective of students in school classrooms. This chapter was developed with an existing dataset to explore different approaches found in the literature to build an index. The results of this chapter showed the need for the development of a survey asking about IEQ general perception, as well as preference, acceptability, and sensation of each parameter. It also highlighted the relevance of equipment selection, pretesting and validation of measured data.

Chapter 6 presents the development and validation of a survey and the data collection protocol developed for the observational part of the study. The final version of the survey (IEQ-F-2) is a validated and reliable tool to evaluate indoor environmental comfort of children in classroom settings and to evaluate the weight given to each parameter on their overall comfort. The tool provides designers and school operators with relevant data from the occupant's point of view. While the results can also, orientate decision-making for the renovation of existing buildings, where the comfort of the children is their most important aim.

Chapter 7 presents the development of an index that summarizes the evaluation of IEQ from the perspective of students. A methodology for the definition of a weighted environmental comfort index for primary schools, based on the study of environmental comfort and the corresponding environmental variables is proposed and validated. A general comfort index was developed through multiple linear regression, which found that the most relevant aspect of IEQ was air quality, followed by noise and temperature, with a neglectable influence of lighting.

Finally, chapter 8 presents the general discussion and conclusions of this PhD thesis. It summarizes the original contributions developed and provides recommendations for future research.

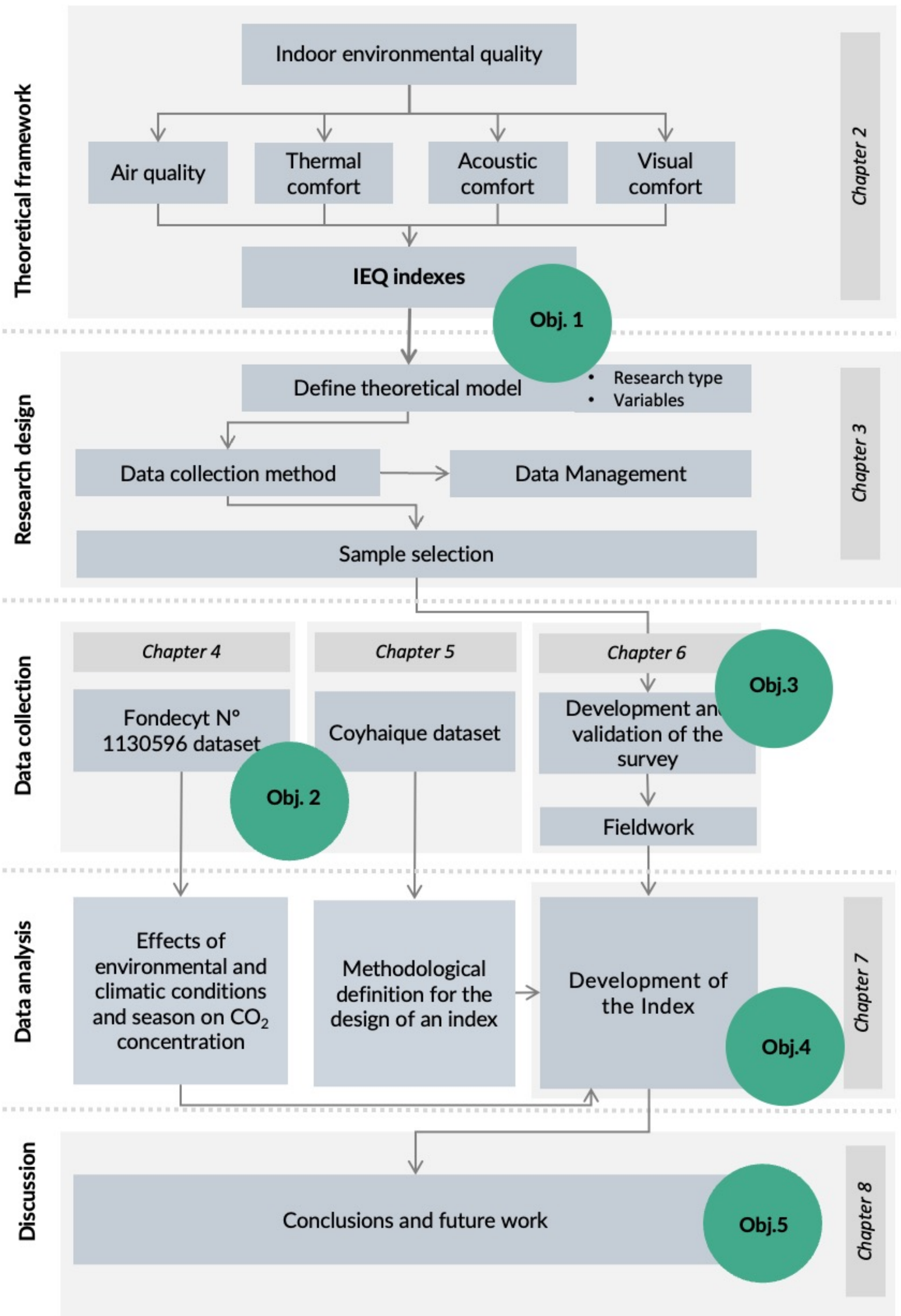

Figure 1.1: *General methodology*

1.7 Original contributions of this research

Journal publication

Diaz, M., Cools, M., Trebilcock, M., Piderit-Moreno, B., & Attia, S. (2021). Effects of Climatic Conditions, Season and Environmental Factors on CO_2 Concentrations in Naturally Ventilated Primary Schools in Chile. *Sustainability*, *13*(8), 4139. https://doi.org/10.3390/su13084139

Conferences

Diaz, M., Piderit, M. B., & Attia, S. (2021). Parameters and indicators used in Indoor Environmental Quality (IEQ) studies: A review. *Journal of Physics: Conference Series*, *2042*(1). https://doi.org/10.1088/1742-6596/2042/1/012132

Book chapter

Diaz, M., Gonzalez-Caceres, A., & Attia, S. (2023). *Multicriteria Design: Optimizing Thermal, Acoustic, and Visual Comfort and Indoor Air Quality in Classrooms* (pp. 435–449). https://doi.org/10.1007/978-3-031-24208-3_30

Posters

Diaz, M., & Attia, S. (2020). Methodology for the evaluation of IEQ in primary school classrooms. *Doctoral Seminar on Sustainability Research in the Built Environment (DS2BE)*. 29-30 June 2020. Online.

2 Indoor Environmental Quality

This chapter presents the state-of-the-art and theoretical framework that supports the definition of this research. It is structured by defining each of the four main aspects of indoor environmental quality and then presenting the measuring techniques used to evaluate each of them. Afterwards, threshold values are presented and contrasted. Once each of the aspects is defined, the literature review of previous work dealing with a systemic evaluation of the IEQ in tertiary buildings is presented.

Lastly, the relevance of the context and other factors that have been found to impact the perception of the indoor environmental quality are reviewed. This chapter ends by presenting the research gap identified, which serves as the starting point of this dissertation.

Part of this chapter was presented at CISBAT 2021 in Lausanne, Switzerland and was published in Journal of Physics: Conference Series (Diaz, Piderit, et al., 2021)

> Diaz, M., Piderit, M. B., & Attia, S. (2021). Parameters and indicators used in Indoor Environmental Quality (IEQ) studies: a review. Journal of Physics: Conference Series, 2042(1), 012132. https://doi.org/10.1088/1742-6596/2042/1/012132

2.1 Introduction

Buildings and their architecture derived from the need to protect humans from the outdoor climate thousands of years ago, this innovation made it possible for our ancestors to live and thrive despite the outdoor environmental conditions. With time, the requirements and expectations of good indoor environmental quality have evolved, as well as the indicators and parameters used to evaluate them. More so, after the global energy crisis of the 1970s, new concerns about the impact that providing a certain level of IEQ in buildings had on the energy consumption of buildings appeared.

The shift in our expectations for how the indoor environment should feel meant that the paradigm from which we evaluate Indoor environmental quality (IEQ) has changed through the years. The prescriptive approach defined standards, and design recommendations to achieve certain thresholds. Afterwards, IEQ has been evaluated in relation to the health and productivity of the occupants, while the latest research deals with the wider concept of wellbeing of the occupants.

In this review, an overview of each aspect of IEQ, indicators and standards, and methods used to evaluate it is presented. Afterwards, a framework for the evaluation of IEQ using multi-criteria evaluation is presented. Finally, identified indexes for school classrooms are described.

2.2 Indoor Environmental Quality

Indoor environmental quality (IEQ) is a broad concept, which seeks to define when a built space provides the necessary conditions for the health and wellbeing of its occupants. This concept groups thermal, acoustic, and visual comfort as well as air quality and depends on multiple factors, which can be classified into four categories; conditions of the external climate, spatial configuration and the envelope of the building, facilities and activities and factors of use (Almeida et al., 2015).

The difficulty in evaluating IEQ as a whole lies in; as stated by Humphreys (2005a): “if a user qualifies a building as "bad" acoustically, but "good" in lighting, the evaluation of the interior environmental comfort will depend on the relative importance that the user gives (based on to the task, experience, among others) to each factor.” For this research, we hypothesize that people do not negatively evaluate the space based on one deficiency, but that in general, they can be indulgent. But knowing when people will be indulgent and if so, with which parameter lies in the variations in human preference and perception.

In response to this issue, Humphreys (M. A. Humphreys, 2005a) concludes that it is not possible to develop environmental comfort indexes that are internationally valid and therefore it is better to continue with unitary analyses. It can be argued that the preference and perception vary for each parameter based on the subject unique background, deeming it useless to define parameters for comfort.

Since the need and usefulness of comfort evaluation schemes have been supported in the literature, an optimistic view will suppose that indexes referring to a specific activity can be developed, which would be equally useful for the design and decision-making, although their applicability would be restricted to the context, as is the case of the specific indexes.

In this sense, the difficulty to assess the multiplicity of factors that influence the perception of environmental quality has been recognized. And the complex relationships between different climatic, spatial, and psychological factors were defined as relevant issues (Huang et al., 2012).

Kim et al.(2012), for their part, state that currently there is no consensus regarding the relevance of the different factors of indoor environmental quality (IEQ) on the perception of the comfort of people.

2.3 Indoor Air Quality

Indoor Air Quality (IAQ) has been related to asthma, allergies, and other illnesses, generally referred to as sick building syndrome (SBS). In classrooms, IAQ becomes more relevant than in other indoor spaces, such as offices, considering the limited area and air volume per student. Low quality of indoor air in schools can lead (directly or indirectly) to health problems, low productivity, and absenteeism (Daisey et al., 2003; M. J. Mendell & Heath, 2005).

There is also evidence that suggests that IAQ is related to cognitive function and productivity and that increasing the ventilation rates in classrooms should improve the academic achievement of students (Haverinen-Shaughnessy et al., 2011b).

IAQ effects on health can be immediate or derived from long-term exposition. Immediate effects appear after a single exposure and normally reside after the exposition is over and can be treatable. The most common symptoms include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue, also, symptoms of some diseases such as asthma may show up, be aggravated, or worsen. Since these symptoms are similar to other illnesses like flu or other viral diseases and vary depending on individual sensitivity, it is very difficult to identify the relation between exposure to pollutants and symptoms.

Long-term effects can appear after long periods of exposure and consist of some respiratory diseases, heart disease and cancer, which can be severely debilitating or fatal. These effects are also very difficult to relate to exposure in specific settings.

The main effects that IAQ has are related to health but also performance, several studies, that will be discussed at large in this chapter, have found a causal relation between performance and IAQ in classrooms.

2.3.1 Pollutants

Although IAQ has been previously studied in schools, the main contaminants, and their effect on children's ability to concentrate, learn and feel comfortable are still not clearly defined, nor universally approved strategies for delivering good IAQ have been defined jet. Currently, a new relevant aspect has resurfaced, the need to control airborne dissemination of the COVID-19 virus inside schools is a relevant topic, that will define the reopening of schools around the world.

Indoor air can contain several pollutants, and their effect on comfort, health and productivity are very difficult to differentiate. A common classification scheme is based on their origin. Dividing them into three main groups; Biological, chemical, and physical.

Biological pollutants are moulds, endotoxins, bacteria, viruses and allergens such as dust mites, pet hair or pollen. While some of them as pollen and bacteria and viruses can derive from outdoor air, others like moulds and fungi can be originated inside and are related to high humidity. Dust mites, viruses and bacteria can be originated inside by people and furniture indoors.

Chemical pollutants include organic and inorganic gasses such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO, NO_2) and ozone (O_3) among others. Volatile Organic Compounds (COVs) are also classified as chemical compounds and most come from construction materials, furniture and cleaning products in school classrooms benzene, toluene, xylene, ethylbenzene, α-pinene, and d-limonene are the most preeminent (Chatzidiakou et al., 2014; de Gennaro et al., 2013; Geiss et al., 2011; Madureira et al., 2015; Safar et al., 2019; Yassin & Pillai, 2019).

Physical pollutants are the common denomination for dust particles between 0.01 – 200 μm, they are further categorized based on their size in Table 2.1. Dust are solid particles that can be temporarily suspended in air and with sizes between 0.1 and 30 μm. While bigger ones can occur, it is unusual for them to remain airborne. Fibres are a particular type of particles that have a different shape (ratio between length and

Hight, and are also considered physical pollutants, from them the most known are asbestos fibres, which are still present in many school buildings and are strongly associated with causing lung cancer if inhaled. Metals can also be classified as Physical pollutants when they are present as particles between 0.1 and 30 μm, in indoor spaces, this is related to old paints that can release lead when chipped or sanded, which could be present in a classroom.

Ultra-fine dust are particles that, due to their size, could pass through the membrane of the lung and get into the bloodstream. The most studied are, tobacco smoke, fumes from cooking, burning candles and heating appliances and dust from laser printers, which should always be located in a separate room. In schools, tobacco smoke should not be present, while heating appliances like wood-burning stoves could be present in some classrooms.

Table 2.1: *Particles*

Denomination	*Size*
Coarse or PM_{10}	<10 μm
Fine or $PM_{2.5}$	<2.5 μm
Ultrafine or nano	<0.1 μm

Radon is a colourless and odourless gas produced by the disintegration of uranium and thorium, present in almost all soils and rocks, and is the second cause of lung cancer worldwide, after smoking. This gas is produced in the soil and can enter the building through cracks in the floor or through the walls. It could also be emitted by construction materials made of soil and stone like bricks, concrete, and natural stone. This gas disappears in the air, but its components can get attached to airborne particles, which are then inhaled reaching the lungs and, if the exposure to it is chronic, can damage the lung tissue and cause lung cancer.

After describing some of the pollutants present in the air, it is relevant to define how the evaluation of the quality of the air is made.

Among all the pollutants the most studied is carbon dioxide, as it is an indicator of ventilation effectiveness that can be measured with relative ease and inexpensive equipment. The measure protocols will be described in Chapter 3 but is relevant to note that the concentration can be calculated based on the indoor occupancy and the decay related to ventilation strategies. The effect of CO_2 concentration on health and performance is still to be confirmed.

Du, et al. (2020) in a review article looking at the cognitive decline linked to carbon dioxide, found that high concentrations (between 1000 and 5000ppm) can affect high-level decision-making performance (measured by the SMS battery), although the methodology used in most of the studies does not allow to eliminate potential confounding factors, this review presents some relevant data to support the idea that

CO_2 is not only a proxy but also a contaminant. In a 2012 experiment, Statish et al. found statistically significant decrements in decision-making performance of adults (2012) related to CO_2 concentrations of 1000 and 2500 ppm. In their review, Mishra et al, found that the effects of CO_2 at building relevant levels are not conclusive (Mishra et al., 2020).

Using CO_2 as an indicator of ventilation rates has been common in research, but its ability to predict indoor pollutants has been discussed. Chatzidiakou et al (2015a) researched to evaluate whether indoor thermal conditions and CO_2 levels within the recommended range can limit indoor exposure to certain pollutants below WHO guideline values. The study was conducted in 18 primary and nursery classrooms in 6 schools in London, UK. Ventilation rates were estimated using metabolic CO_2 decay as a tracer gas under normal conditions and intervention studies, where windows were closed, and ventilation rates were assumed to be the same as infiltration rates. In this research, evidence was given of the suitability of the use of CO_2 as a marker for IAQ, considering that controlling for indoor CO_2 levels may lower over-heating and dilute pollutants with indoor sources. Two assumptions are made here, related to the specific climate under study that need to be acknowledged. First, overheating risk will be lowered if the outdoor air is colder than the inside air and second, if outdoor pollution sources are neglectable.

2.3.2 Performance and Indoor Air Quality in Schools

Performance is a wide concept that encompasses the ability to perform certain tasks properly. Considering the time spent performing a task (productivity) and if they perform it correctly. Bakó-Biró et al., (2012) incorporated mechanical ventilation in existing classrooms to deliver different ventilation scenarios while students performed a set of quizzes included in the VISCoPe computer-based assessment test. The ventilation equipment either recirculated air or replaced it with outside air at a given rate. They demonstrated a diminished performance of school children in poorly ventilated classrooms. They also found a faster reaction time when temperatures were comfortable compared with the existing slightly elevated levels. They propose a ventilation rate in the order of 8 l/s per person to prevent any impairment of pupils 'performance related to poor ventilation.

With a completely different approach, Haverinen-Shaughnessy et al., (2011a), studied the relationship between CO_2 concentrations during occupied hours and standardized test score results of students in 100 classrooms in the southwest United States. These classrooms had Heating, ventilation, and air conditioning (HVAC) systems on during measurement. The results suggest a linear association between substandard ventilation in a classroom and lower academic achievement. Since the research is unable to control for confounding factors, a causal relationship between both variables cannot be defined.

Sick building syndrome (SBS) refers to a series of symptoms (airway irritation or congestion; headache, tiredness, sensation of getting a cold, nausea; and eye irritation/swollen eyelids), that are prevalent inside the buildings but disappear when people leave it. Norback et al., (1990) reported on the prevalence of such symptoms in six primary schools. In a review article, Daisey et al., (2003) identified two papers that correlated the presence of Formaldehyde, VOCs and other contaminants with Asthma prevalence.

2.4 Thermal comfort

Thermal comfort refers to acceptable indoor thermal conditions from the perspective of the occupants. The first model to define these expectations was developed by Fanger (1970) and considers both environmental factors (temperature, thermal radiation, humidity and airspeed), and personal factors (activity and clothing). An expanded definition of comfort understands that heat balance is not the only parameter that affects the perception of thermal comfort, but expectations and thermal preferences play a role in acceptability (M. Humphreys & Nicol, 1998). For this definition, the physical, climatical and cultural context of the occupant plays a big role in their satisfaction (R. J. de Dear & Brager, 2002). Furthermore, the adaptative comfort model proposes that the occupants can perform a series of activities that will enhance their satisfaction. This idea is summed up in the adaptive principle: *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* (J. F. Nicol & Humphreys, 2002, p. 564). The strategies that occupants can use to adapt to the thermal environment can be categorized into five types of behavioural actions (J. F. Nicol & Humphreys, 2018)

1. Regulating the rate of internal heat generation (e.g. change activity)
2. Regulating the rate of body heat loss (e.g. changing clothing)
3. Regulating the thermal environment (e.g. open a window, turn down the heating)
4. Selecting a different thermal environment (e.g. move to another room, go out)
5. Modifying the body's physiological condition (e.g. Vaso regulation, sweating, shivering and changes of posture)

Indoor environments depend on teachers' preferences (De Giuli et al., 2012), this means that children must accept indoor conditions. Many factors can explain why students may have a different perception of thermal comfort than teachers. Firstly, it has been identified that children have a different perception of thermal satisfaction than adults (Teli et al., 2013). In their review article, Zomorodian et al.(2016), found that in general, students prefer cooler environments and are more sensitive to warm conditions than expected when compared with comfort models designed for adults. Teachers, tend to have lower activity than students during the entire school day, whereas children have high activity during gym classes and when playing during recess (Teli et al., 2012). These high activity periods should have an impact on the rate of internal heat generation during schooldays. Another factor is that students have limited options to regulate the thermal environment, as they cannot change to another room or go outside whenever they feel uncomfortable. If students want to open or close a window, it is common to ask for verbal authorization from the teacher, who can also veto this change based on their own preference. Lastly, and maybe specific to the Chilean scenario, students wear uniforms. In some cases, the uniform is defined for winter and summer[5], meaning that they have very limited options to regulate the rate of body heat loss.

The neutral temperature of children has been found to differ from predicted for adult subjects (Teli et al., 2013). In their review article, Zomorodian et al. (2016), identify that the preferred temperatures are not exactly the neutral thermal sensation of respondents and are 1.5–4°C lower than the neutral temperature in most studies. They also identified great variation in neutral temperature between studies. Ranging from 16.7°C for free-running schools in Chile (Trebilcock et al., 2017b) to 29.5 °C in naturally ventilated schools in Taiwan (Liang et al., 2012). The variation could be explained by the adaptation to the climate and expectations of the students. It is relevant to note that the lower neutral temperature was identified in free-running schools. Chilean regulation does not require heating in part of the country although outside temperatures are outside comfort, thus could affect the expectations of the students.

2.4.1 Performance and Indoor thermal comfort in schools

Several studies have tried to link the performance of students with the temperatures inside the classrooms. This idea is relevant because children's learning process is of furthermost relevance for schools, teachers, parents, and children themselves. Most studies focus on the effects of high temperatures on learning since this is an issue in most temperate climates. Developed countries, especially in temperate climates have heating in their schools, and therefore low temperatures are not an issue. In their review article, Wargocki et al., (2019) state that there are no studies on performance with temperatures lower than 20°C. Although temperatures under 20°C can be

[5] This statement is based on informal interviews with students. It has been backed up by reviewing school regulations.

uncomfortable for adults, the before mentioned studies found that school children can be comfortable at lower temperatures.

In their review, they conclude that the relationship between thermal comfort and performance is described by the following equation, but only applicable for temperatures between 21.8°C and 29.5°, according to Eq. 2.1. where t is the air temperature and y is the relative performance in percentage.

$$y=0.2269t^2 - 13.441t + 277.84 \qquad \textit{Eq. 2.1}$$

According to Eq. 2.1, air temperatures of 22°C correspond to 92% of relative performance, while temperatures of 28°C to 86% of relative performance.

2.5 Indoor acoustic comfort

Acoustic comfort is the sensation of wellbeing in a sound space, that ensures that the activities that ought to be made can be performed without stressing the voice or generating acoustic overstimulation. In this sense, a good sound environment is defined as one where external and internal noise is minimized and good communication is ensured by having acceptable intelligibility for teaching and learning.

Contrary to the case of air quality, thermal and visual comfort, there are few adaptative possibilities for acoustic comfort. Taking as an example the strategies categorization proposed for thermal comfort (J. F. Nicol & Humphreys, 2018), it is observed that students have little control.

1. Regulating the rate of noise generation (e.g. Asking others to stop making noise)
2. Regulating the acoustic environment (e.g. closing a window)
3. Selecting a different acoustic environment (e.g. move to another room, go out)

They cannot control the rate of noise generation since noise is produced by others, being outside sources or indoor sources. There is no equivalent to changing the rate of body heat loss. Students could use noise-protecting devices, but they would also lose the ability to hear the teacher or other meaningful sources of oral communication. One way they must control the noise is by regulating the acoustic environment, by closing windows and doors. Selecting another acoustic environment, although in theory feasible most certainty is against school regulations and would also mean that they don't participate in the class. This inability to control the acoustic conditions generates frustration and in turn makes noise one of the main causes of stress in city life (Basner et al., 2014).

Acoustic comfort has a greater relevance in schools and classrooms than in other buildings because most of the work and communication in these settings is performed orally. It is relevant to consider that the ability to recognise speech from noise matures with age, therefore for small children, it will be more difficult to hear and understand what the teacher is saying in a noisy environment than what the teacher can evaluate based on their own abilities (Talarico et al., 2006). Speech intelligibility, defined as 'that aspect of speech-language output that allows a listener to understand what a speaker is saying'(Finitzo-Hieber & Tillman, 1978), manures with age. At the same time, children have difficulties understanding degraded speech[6] and staying focused on a cognitive task in the presence of distracting noise (Klatte & Hellbroock, 2010).

In school settings, it has been found that a relevant part of the noise is produced inside the classroom by their own occupants (P. M. Bluyssen et al., 2020). Other noises from inside the classroom but not directly generated by the occupants are noises from ventilation equipment, lighting, or projectors.

For inside-generated noise, the main determinant of a room's acoustics is the reverberation time (RT) meaning, the persistence of sound after the sound source has stopped7. This value will be affected by the volume of the scape and the absorption of the finishing materials. High reverberation time (RT) means that undesired sounds as moving chairs, scraping feet, coughing, and other sounds, remain longer in the room (Klatte et al., 2010). Also, when in group work, the "coffee shop effect" will make each group compete with the noise from the others.

Noise coming from outside the classroom will be another determining factor of acoustic comfort. Schools need to be in urban areas that ensure accessibility and coverage, but this can have a detrimental effect on the sound environment. Using Santiago de Chile as an example, 71% of the schools in this city are located in high environmental noise areas, that if not treated properly could affect the teaching-learning process (Aguilar, 2019). Other sources of outside noise are adjacent spaces such as classrooms, yards, and circulation spaces.

To counteract the noise from outside, acoustic insulation of the envelope is usually required. As described before, the noise environment can differ from location,

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[6] Or degraded hearing, when the signal is not strong enough to be clear or parto of the message is lost.

[7] Time in seconds required for sound pressure at a specific frequency to decay 60 dB after the sound source has stopped.

therefore the insulation needed should also be adapted to outdoor conditions. To evaluate the effectiveness of the insulation the Noise Level (L_{eqAS}) indicator is used.

The excessive use of insulation can cause dissociation from outdoor conditions, and although noise from the road and aerial traffic is disruptive, natural and anthropic sounds can be perceived as positive. The extreme reduction of environmental information can generate anxiety (Stockfelt, 1991)

2.5.1 Performance and acoustic comfort in schools

In school classrooms, performance and acoustic comfort are closely interconnected. The acoustic environment has a significant impact on impacts students' learning, concentration, and overall academic performance. Acoustic comfort can influence teacher-student communication, concentration and focus.

Klatte et al. studied 17 classrooms with reverberation times ranging from 0.49 to 1.11 seconds and found that children had the worst performance on a phonological processing task[8] in classrooms with long reverberation compared to short reverberation. In their review Mealings (2022) found that chronic noise exposure has adverse effects on the literacy of children, being on reading comprehension, speed, and accuracy. This review also suggested that noise level (LeqAS) should not exceed 38 dBA.

2.5.2 Indicators and metrics

The main indicators used to describe the acoustics of a classroom are Reverberation Time (RT) and Background Noise Level (L_{eqAS}), Speech Transmission Index (STI) and Signal-to-Noise Ratio (SNR). The required values for each of them are presented in Table 2.2.

[8] A task were students need to identify, analyze and storage sounds of their own language (German for this study). This sounds can include spoken words and nonwords.

Table 2.2: *Acoustic requirements for classrooms (adapted from* (Ipinza et al., 2023)

STANDARD	COUNTRY	L_{EQAS} (DBA)	RT (S)	STI
MINEDUC	Chile	-	0.6 - 0.7	0.6
BB93	UK	30-35	0.6 - 0.8	-
ANSI S12.60	USA	35	0.6 – 0.7	0.6
BR15	Denmark	30	0.6	0.6
SS025268	Sweden	26-40	0.6	0.6
NBN 01-400-2	Belgium	35	0.35 log	-

From a systematic review, it was found that poor acoustics in classrooms are common even in countries where legislation is in place (Gheller et al., 2020). Without contesting the possible causes of this problem, they argue that unoccupied noise levels and RT are good parameters to evaluate the quality of the acoustic environment. They also suggest that the unoccupied noise levels influence background noise and RT measured during classes.

2.6 Indoor visual comfort

Visual comfort refers to the quantity and quality of natural and/or artificial lighting that allows us to perform a task in a space in a comfortable way, while clearly distinguishing colours and avoiding glare. The aforementioned description deals with the light part of comfort, but visual comfort also includes the connection with the outside and the visual quality of the surrounding space.

The first parameter to consider is natural light as it has better chromatic reproduction and controls our circadian cycle, while also lowering energy demand so it should be prioritized. School buildings should be designed to foster the use of natural light, as, in the case of children and adolescents, the operation of the building tends to coincide with the daylight hours. It should be considered that the variability of daylight, both during the day and through the year gives complexity to the design of spaces that profit from natural light. Therefore, the need for case-specific natural light control strategies.

It is equally relevant to the connection with the outside, as this positively affects the quality of life in school spaces and allows us to accommodate the vision using distance as a tool. The view part of visual comfort is related to the need for connection to the environment, whether it is nature or a view of the city. There are proven benefits to visual connection to the outside (Kent & Schiavon, 2020). Specific to schools, a view of nature has been linked to children's wellbeing (Lindemann-Matthies et al., 2021) and learning outcomes (Heschong Mahone, 2002). This indicator of visual comfort has been included in standard EN 17037 2018.

It should be considered that educational spaces operate mostly in periods with the availability of natural light, but often the support of artificial lighting is needed, which must deliver the appropriate lighting levels to the tasks of the enclosure, be uniform and have a good chromatic performance and colour appearance.

2.6.1 Indicators and metrics

The indicators used to describe the visual aspects of a classroom generally represent the amount and quality of light. To be more precise, the quantity of light that is related to discomfort could be too little, meaning that the occupant cannot see enough to complete the task or too much, meaning that the excess of light makes it difficult to complete a task. A third indicator that deals with the quantity of light is its uniformity, as patches of light with high contrast are uncomfortable. Quality of light can be described through colour rendering, meaning that the user can see the colours as they would present under natural light. The colour of the light is also relevant, especially with LED artificial lighting.

The excess of light can also have detrimental effects. Glare is defined as "a condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts" (Society of Light and Lighting CIBSE, 2018). It can be categorized into two types: disability glare, which impairs vision, and discomfort glare, which causes discomfort without necessarily affecting vision. Glare can be caused by direct sunlight, reflections on glossy surfaces, or poorly designed lighting systems.

Considering the complexity of the perception of light and the different lighting needs depending on the intended use of space, several metrics have been developed. The metrics relevant to the design, evaluation, and optimization of visually comfortable and efficient indoor environments in school classrooms are presented as follows. Some thresholds included in Chilean and international normative are presented in Table 2.3.

Table 2.3: *Visual requirements for classroom*

STANDARD	***REQUIREMENT***	
OGUC[A]	window sized x % of floor area	(Art.4.5.5)
DE. 548[B]	180 Lux	(Art.9.10.b)
TDRE[C]	>300 Lux	
CES[D]	FLD≥ 2 or	UDI > 30% occupied time (100 to 2000 lux) or sDA > 40% occupied time
EN16798-3[E]	500 lux	
DQLS[F]	UDI between 300 to 2000 lux for 80% of school hours across more than 50% of the usable floor level	

Illuminance (Lux): Illuminance measures the amount of light on a surface and is expressed in lux. It is usually measured on the horizontal work-plane, with the height of a worktable. It is essential for tasks that require good visibility and visual acuity. Adequate illuminance levels are necessary to prevent eye strain and discomfort. To ensure comfort, it should also consider the contrast with the illuminance in their immediate surroundings. For the evaluation of classrooms vertical eye illuminance can also be considered on the wall that has the whiteboard.

Daylight Factor (DF): DF represents the ratio of indoor illuminance at a point on a horizontal surface to the outdoor illuminance under overcast sky conditions. It helps to assess the amount of daylight penetrating indoors and aids in optimizing the use of artificial lighting.

Spatial Daylight Autonomy (sDA): sDA evaluates the percentage of floor area that meets the target illuminance levels from natural daylight during occupied hours. It provides a comprehensive assessment of daylighting conditions in an indoor space.

Daylight Autonomy (DA): measures the percentage of occupied hours during which a space receives sufficient daylight to meet the target illuminance levels without the need for artificial lighting. It helps to design spaces that rely on natural daylight and reduce energy consumption. It has the disadvantage that it does not account for excessive light.

Useful Daylight Illuminance (UDI): This is a response to DA, in that it represents the percentage of occupied hours when a target range of illuminances is met at a point in a space by daylight (Nabil & Mardaljevic, 2006). The ranges defined as desirable e are usually between 300 and 3000lux.

Continuous Daylight Autonomy (DAcon): gives partial credit to time steps when daylight illuminance lies below the minimum. The advantage of this metric is that it recognizes the variability of daylight and humans' adaptability to it. Instead of a hard threshold, the transition between compliance and noncompliance becomes softened(Reinhart et al., 2006).

Daylight Glare Probability Index (DGP): calculates glare based on vertical illuminance and contrast effect (relationship between source luminance and task) (Wienold & Christoffersen, 2006). This indicator is used in the EU standard EN 17037 – Daylight in buildings (Comité Européen de Normalisation, 2018).

The described indicators and metrics are used in the design, evaluation, and optimization of daylight use and lighting systems to create visually comfortable and efficient indoor environments. Proper consideration of these indicators can enhance occupant satisfaction, productivity, and well-being in various indoor settings.

2.6.2 Performance and visual comfort in schools

The quality of the visual environment can significantly impact students' learning, concentration, and overall academic performance, as most of the teaching-learning process relies on looking at the whiteboard, presentations, and reading. Seeing the speaking person is also relevant for understanding the spoken words and giving them context. Visual comfort can influence reading and comprehension, visual Acuity, colour perception and task performance. Researchers have found a correlation between Light colour temperature, visual comfort, and task performance (Shamsul et al., 2013). In their research they measured performance as typing speed and accuracy, The results show that speed was improved under cool white light (CWL) compared with warm white light (WWL) which was also perceived as least comfortable. artificial daylight (DL) was observed to result in the least typing errors. This study was performed in a laboratory and although the results coincide with previous studies, they are still exploratory. No studies correlating visual comfort and performance in school classrooms were found in this review.

2.7 Measuring; Subjective and objective methods

At the international level, there is no consensus on the methods, indicators, and equipment to be used for the evaluation of IEQ (Heinzerling et al., 2013b). In general, the methods used in the literature can be described as subjective and objective methods.

2.7.1 Subjective measurement methods

The most used method to evaluate the subjective perception of comfort is surveys. The sampling used can be done via transverse – where a large group of people are polled once over a limited period of time-, or longitudinal –where a smaller group of people is surveyed repeatedly over time.

Transverse sampling allows gathering data under the different conditions that could arise during the day, changes in solar penetration, indoor temperature, noise, and ventilation patterns. The main drawback of transverse sampling is that subjects get tired and bored after being surveyed many times (M. Humphreys et al., 2015). At the same time, the results may be non-generalizable and reduce the number of buildings or spaces surveyed.

Longitudinal sampling, on the other hand, needs a bigger group of people, and if applied once, would only represent one specific environmental condition. This type of sampling has the advantage of being less disruptive to the subjects, as they are interrupted only once to complete the survey. This type of survey could be applied in many buildings and spaces, although the generalizability of the results is still problematic.

Surveys are cheap to apply (compared with measurements), and the information gathered will reflect the perception that the occupants have of the environment. The relatability of the surveys will depend on various factors:

- Personal
- Survey design
- Survey application
- "experiment" design

Most of the existing surveys to evaluate Indoor Environmental Quality have been developed in industrial countries to be applied to Post Occupational Evaluation (POE) of office buildings. Some relevant examples are the BUS occupant survey, which was developed in the UK and allows to benchmark of office buildings against an ever-growing database of case studies (Leaman & Bordass, 2001). This survey is also applicable to residential buildings, as is the CBE survey, developed by the Centre for the Built Environment in Berkley (Frontczak et al., 2012). CBE survey consists of a toolkit with an occupant satisfaction survey and a scorecard report generation tool (Zagreus, Huizenga, et al., 2004) and had been applied in more than 600 buildings until 2014 (Galatioto et al., 2014). The HOPE project (Health Optimisation Protocol for Energy-efficient Buildings) also produced a survey to evaluate the perception of the indoor environmental quality of office occupants in 60 European office buildings and 96 apartment buildings were surveyed (Roulet et al., 2006).

Some surveys have been developed to study IEQ in schools. Auliciems (1969), studied thermal comfort in 11- to 16-year-olds at school while Humphreys (1977a) did the same with primary school children. The latter used a simple form with transverse sampling four times a day for four days. The teacher also completes a form with information about the willingness of the students to participate in the survey. It is relevant to note that "fewer than half the children in the sample proved to be capable of using the thermal comfort rating scale to provide information sufficiently reliable for analysis." (M. A. Humphreys, 1977a, p. 237). More recently, De Giuli demonstrated that children (ages 9-11) were able to answer an IEQ survey.(De Giuli et al., 2012). Research on thermal comfort (Korsavi & Montazami, 2019a; Mors et al., 2011; Teli et al., 2012; Trebilcock et al., 2014) found that children were able to respond to sensation questions for indoor temperature.

2.7.2 Objective measurement methods

To evaluate the physical parameters related to IEQ, different equipment can be used. For field studies, there is no consensus on the length of measurement. Different publications have periods of 3 days to months of measurements, depending on the objective of the study.

2.8 Methodologies and indicators used in the evaluation of IEQ in classrooms

At the international level, there is no consensus on the methods, indicators, and equipment to be used for the evaluation of IEQ (Heinzerling et al., 2013b); the reviewed studies can be classified grosso modo into qualitative, short period quantitative and longer period quantitative studies. Research on school buildings focuses on the classroom unit and evaluates different parameters as shown in Table 2.4.

Bluyssen et al. (P. M. P. Bluyssen et al., 2018) evaluated comfort and health levels in school classrooms using data collection tools based on the SINPHONIE research project. De Giuli (De Giuli et al., 2012), conducted evaluation campaigns of seven schools near Venice, Italy in springtime. Their subject was 614 children aged 9 to 11, who completed a questionnaire about IEQ in the classroom and the impact on their psychological wellbeing. At the time of answering the questionnaires, measurements were collected every 15 seconds. The survey was conducted on paper with the supervision of a researcher, which achieved 87% of response rate. On the other hand, the monitoring of environmental parameters was considered very short. The results showed that noise is the main complaint among students. Another interesting result is that all environmental parameters were evaluated better in alternative schools (Waldorf, etc.) than in traditional schools. One could propose a relationship between the incorporation of dynamic teaching-learning methodologies and the consequent adaptation of classroom use, and greater control and autonomy on the part of students, who could manipulate elements such as windows, move within the classroom or modify the type of clothing, without affecting the development of the class which would improve your perception of comfort by having a greater ability to adapt.

Barrett et al. (Barrett et al., 2015) performed surveys and semi-structured interviews with teachers and a photographic survey and description of the space in 153 classrooms in 27 schools. For the spatial definition, researchers defined 30 factors to study based on 18 indicators divided into three design principles (Table 4). The data collected were contrasted with the results of the students' school performance through a multi-level statistical model (MLM). This statistical model was used to find correlations between the spatial and comfort qualities of the classrooms and the performance of the students.

The main result presented is that "... the physical characteristics of the primary schools impact the progress in reading, writing and mathematics". This impact is quite high, explaining 16% of the variation in the overall progress during a year of the 3766 students who participated in the study.

It is noteworthy that the research of Barrett et al. presents an expanded spectrum of factors that influence school performance beyond studies that have focused only on indoor environmental quality (IAQ). Another relevant factor is that, in the case of elementary students, the classroom is very relevant to performance. No direct relationship between the spatial quality of the whole school and performance was found. In general, Barrett’s research envisages a relationship between spatial quality, viewed from a holistic perspective and school performance. It is important to point out that the results cannot be extrapolated to other realities. The authors argue that the relevance of the factors should be linked to aspects of infrastructure quality, culture and permanence in space, among others.

Table 2.4: Overview of studies of IEQ in classrooms

Study/protocol	*Acoustics*	*IAQ*	*Lightning*	*Temperature*	*Comfort*
Diaz et al., 2021(2021) *8 classrooms, 3 days in winter and spring Measurements @30 min*	--	CO_2	--	Radiant Temperature Relative humidity	Not included
Korsavi et al., 2020 (2020d) *32 classrooms, Measurements @5 min and time-lapse cameras.*	--	CO_2 Airspeed	light levels	Air and radiant temperature Relative humidity Air speed	children's sensation votes on the thermal environment, IAQ, visual environment and overall comfort. Developed in (Korsavi & Montazami, 2019b)
Bluyssen et al. 2018(2018) *37 classrooms. Measurements @15 sec.*	--	CO_2	--	Temperature Relative humidity	Children's Building Symptom Index Children's Personal Symptom Index Children's Building comfort index
Sadick et al. 2017(2017) *32 schools. Sample measurements*	Background noise dB(A) Reverberation time (RT60 at 1KHz)	CO_2	Daylight factor	Temperature Relative humidity	1. Semi-structured interviews with teachers 2. online survey and sample measurements
Toyinbo et al. 2016 (2016) *108 classrooms Several weeks of summer.*	--	CO_2	--	Temperature Flow	Questioners to principals of the schools and students
De Giuli et al. 2012 (2012) *28 classrooms. measurements*	--	CO_2	Emin (lux) Emax (lux) On/off Shadings up/down	Air temp Relative humidity Globe temp	51 questions questionnaire
Barrett et al. 2015(2015) *27 school. Spot measurements*	Noise levels	CO_2	Illumination levels	Air Temperature Relative humidity	Architectural measurements questionnaire-based interview

2.8.1 Multicriteria indexes

Multicriteria indexes are a response to the fact that multiple factors contribute to the overall quality of the indoor environment. Therefore, it is relevant to understand them in an integrated manner, rather than assessing these factors individually, providing a holistic evaluation of the environment.

There have been several methods applied to develop an index. Most of them use a survey, to then weigh each aspect of IEQ using different statistical analyses **Table 2.5**. In their review article, Leccese et al. (2021) identified the following statistical analyses:

Analytic Hierarchy Process (AHP)

Is a structured technique for evaluating complex decisions in a group decision-making. This technique is used in scenarios where the complexity of the problem makes the decision unclear. AHP decomposes the problem into a hierarchy of more easily comprehended sub-problems, to be then analysed independently by a group of experts.

Multiple Linear Regression (MLR)

This model describes how a dependent variable, in this case, comfort, depends linearly on several predictor variables.

Non–Parametric Spearman Correlation Analysis (NPSCA)

This technique organized variables into ranks and then looks at the correlation between two sets of ranks. This means that the correlation coefficient uses only the ranks of the values and not the values themselves. Through this transformation, we can evaluate and compare ordinal and continuous variables. For the interpretation of this correlation, it is relevant to note that the resulting values will lie between -1 and +1. When the observations are given exactly the same rank, then the resulting value will be 1, if they are assigned exactly the opposite rank, the resulting value will be -1. In both cases, we will see a strong correlation, in the first case a positive and in the second case a negative correlation. When the resulting coefficient approaches 0, it indicates that there is no found correlation. Even if the correlation coefficient is zero, a non-linear relationship might exist.

Multiple Non–Linear Regression

This model describes how a dependent variable, depends non-linearly on several predictor variables. Observational data are modelled by a function which is a nonlinear combination of the model parameters. The data are fitted by a method of successive approximations, and the curve can take almost any form.

Multivariate Logistic Model

This type of model is used to predict the relationships between dependent and independent variables by calculating the probability of something happening depending on multiple sets of variables. This is a common classification algorithm used in data science and machine learning.

Pearson Correlation Analysis

This coefficient will only reflect linear correlations and can only be applied to “either two continuous or two ordinal variables or a combination of an ordinal and a continuous variable, but not for two nominal variables” (Heumann et al., 2016, Chapter 4.3.3). Pearson’s coefficient uses the entire information contained in the continuous data.

Proportional Ordinal Logistic Regression

Proportional odds logistic regression can be applied when there are more than two outcome categories that have an order, either discrete or continuous. An important underlying assumption is that no input variable has a disproportionate effect on a specific level of the outcome variable.

Binary Logistic Regression

This technique can be applied when the dependent variable is categorical or has been turned into a categorical dichotomous[9] variable, where both categories are mutually excluded. When using this technique, it is possible to evaluate the impact of multiple independent variables that are present simultaneously on the dependent variable.

Selection of models

The selection of the model depends firstly on the objective of the research. Then, the characteristics of the available data. Depending on the type of data (continuous, categorical, ordinal), the number of criteria or variables, and the measurement scales. Then it should be studied the relationship between factors. Linear relationships, nonlinear relationships, or complex interactions among the dependent variable and its predictors should be considered. Special attention should also be given to the size and quality of the dataset.

A model to represent IEQ will be built based on data gathered through survey questions. If the questions are arranged on a Likert scale, the data would be ordinal. In this type of categorical data, the categories have a meaningful order or ranking but lack a consistent numerical distance between them. In the case of a Likert scale, respondents are asked to rate their level of agreement or disagreement with a statement or question using a predefined set of response

[9] 2 categories

options, typically ranging from "Strongly Disagree" to "Strongly Agree." Since we cannot prove that the distance between Agree and strongly agree is the same as between disagree and strongly disagree are the same, the data cannot be treated as interval or ratio data. This limits the available statistical analyses.

Linear regression, for example, should not be used when the dependent variable is ordinal data, as it violates the assumption of linearity. However, some researchers still use this technique by assuming that the data is continuous. In this case, it is advised to use ordinal regression (also known as ordinal logistic regression) when dealing with ordinal data as the dependent variable. Ordinal regression is specifically designed to handle ordinal outcome variables and can model the cumulative probabilities of each response category based on the predictor variables. Binary logistic regression is also an ordinal logistic regression but with only two possible outcomes.

Lastly, Pearson Correlation Analysis, assumes that the correlation between two variables (either two ordinal, two continuous or a combination of both) is linear. If the linearity of the relation can be established, then Pearson's could be used.

Table 2.5: *Values given to each coefficient in the literature and method used to develop the index. Based on* (Leccese et al., 2021)

	thermal CT	***air quality CIAQ***	***acoustic CA***	***visual CV***	***method***
Astolfi and Pellerey (2008) [a]	0,33	0,21	0,26	0,2	PCA
Cao et al. (2012) [a,c]	0,38	0,14	0,27	0,21	MvLR
Lee et al. (2012) [a]	0,22	0,18	0,39	0,21	MvLgR
Catalina and Iordache (2012) [a]	0,25	0,25	0,25	0,25	MNLR
Ghita and Catalina (2015) [a]	0,27	0,3	0,19	0,24	-
Thasildoost and Zomorodian (2018b) [b]	0,34	0,09	0,26	0,31	PCA
Buratti et al. (2018) [b]	0,35	--	0,35	0,3	PCA
Fassio et al. (2014) [b]	0,33 [x]	0,10 [x]	0,18 [x]	0,38 [x]	MvLR
Leccese et al.,(2021) [b]	0,43	0,17	0,16	0,24	MvLR
Average	0,3	0,2	0,26	0,24	

[x] different weight depending on time of survey. 11:30 is presented.
[a] school classroom, [b] university classroom, [c] Public/office building
PCA: Pearson Correlation Analysis, MvLR: Multivariate Linear Regression, MvLgR: Multivariate Logistic Model AHP: Analytic Hierarchy Process.

2.9 Chapter conclusions

- The aim of reducing energy demand could negatively affect the ventilation of classrooms. Thresholds for ventilation per student should be defined, designed for, and evaluated after the building is in use. As it has been proven that proper ventilation has an impact on the performance of the students.
- There are no studies that relate temperatures lower than 20°C with performance and health. This should be addressed as school children are comfortable at lower temperatures. Which could in turn lower operational costs and improve energy efficiency.
- The behaviour of the occupants can help cut energy use, while maintaining satisfaction (J. F. Nicol & Humphreys, 2018)
- There is no definitive definition of acoustic comfort
- Noise can be generated indoors or outdoors, and different strategies need to be used to control it.
- Students have no adaptative strategies to cope with noise. At the same time, most of the teaching-learning is made orally, therefore it should be a main focus to enhance IEQ and encourage learning.

2.9.1 Research gaps

Researchers have demonstrated a correlation between high temperatures and diminished performance. It is not clear if there is a cap on low temperatures. This is relevant to lower energy demand for heating. No survey to address the IEQ evaluation by school children was found in the literature review.

Multi-criteria evaluation of IEQ is a topic in development in the last years. No index has been defined to evaluate IEQ and there is discussion on the weighting of each parameter. There is a need to establish a clear methodology for the evaluation of IEQ from a multicriteria perspective.

3 Methodology

3.1 Introduction

This chapter presents the research methods used in this PhD. It first presents the *Contextual limitations* that redefined the scope of the PhD. Afterwards, the *Research design* is explained.

Then, the *Sample selection* process is described for all case studies, defining the advantages and constraints of each case study. Special attention is given to *the Socio-Environmental context* of the study and the characteristics of the climate.

Afterwards, *Data management,* presents the process of anonymization and data cleansing applied to ensure the quality of the data and the accuracy of the tools used for measuring and surveying. The last subchapter *Statistical methods,* presents the statistical methods and analysis used in this research to find correlations between measurements and surveys and between the four aspects of Indoor environmental Quality.

The main result of this chapter is a mixed methodology comprising empirical, modelling, qualitative and quantitative research. This methodology will develop a framework to build a multi-criteria index to evaluate IEQ in school classrooms. The research is based on a sequential approach to the problem, increasing the complexity of the problem in each stage, to finally develop a Methodology for the evaluation of Indoor Environmental Quality and Comfort in school classrooms through a multicriteria index.

3.2 Contextual limitations

This research was conducted between 2018 and 2021. The COVID-19 (acronym of Coronavirus Disease 2019) pandemic affected the validation of the developed survey (chapter 6), and the surveying of children in their classrooms. The Chilean response to COVID-19 meant that schools stopped having in-person classes from 15th March 2020, after the declaration of a global pandemic by the World Health Organization (WHO) on 11th March 2020. It is relevant to note that the school year starts around 5th March in Chile, after summer vacations between the end of December and February. This closing of educational establishments had several implications for the health, wellbeing and learning of children that are beyond the scope of this investigation and are described in the report by the Ministry of Education of Chile (Mineduc) (2020).

For this research is relevant that children did not use their classrooms during this time, they studied online from their own homes, under heterogeneous environmental conditions. The first attempt to open schools was on the 1st of March 2021, with a backlash from parents and society in general due to the high number of COVID-19 infections detected in the first days (Deutsche Welle, 2021). In June 2021, a second attempt to return to in-person classes focused on a voluntary return to school. The protocol to return to class (Ministerio de Educación Chile, 2021), included measures like ensuring 1m of distance between students in class, opening of window and use of winter clothes during classes to avoid the cold. The studied schools had to divide classes in two so that the 1m requirement was met. Meaning that children will have in-person classes every other week.

These measures and the voluntary character of the in-person attendance to schools meant that classrooms in the case study had between 0 and 6 students per classroom (between June and August) from the 40 students that will normally attend each.

The constraints due to COVID-19 affected the proposed methodology, which was adapted under high uncertainty in March 2020. Therefore, it was decided to work with secondary data from existing databases to explore the interactions between different parameters of the IEQ (Chapter 4) and perform an exploratory correlational analysis between thermal, acoustic and air quality indicators and perception of comfort (chapter 5)

These exploratory studies built the foundation for the development and validation of the survey and provided empirical validation to the theoretical definition of the index (chapter 7).

The limitations related to the adaptation of the methodology to the COVID-19 pandemic will be further discussed in this chapter.

3.3 Research design

The main objective of this research is to develop an indicator that will allow *weighting the relevance of the four aspects of IEQ*, concerning the general comfort of students in school classrooms, allowing the evaluation and comparison of the quality of the spaces. The independent variable in this case is the environmental comfort of the students, while the dependent variables are indoor environmental factors.

The research paradigm in which the research is framed is post-positivist using a mixed method comprising empirical, modelling, qualitative and quantitative research, as presented in Figure 3.1.

The *empirical* part of the methodology will consist of a literature review of key topics for the research, such as POE of buildings, survey design to evaluate occupants` perception and measurement protocols for IEQ. As well as key indicators of thermal, acoustic, illumination and air quality indicators and thresholds (Chapter 2).

Modelling will be used to develop a survey adequate to evaluate indoor environmental quality of children in school classrooms, that will allow conducting a multivariable analysis to identify interactions between parameters on the overall perception of comfort in the classroom. This survey will be designed to find a definition of the forgiveness factor for this typology (Chapter 6).

Quantitative methods will be used to measure indoor environmental quality parameters to then determine comfort ranges for each of the components of IEQ. The before-mentioned survey will be used to evaluate the perception of comfort of students in their classrooms (Chapter 7).

Then correlational research (A. Field & Iles, 2016) between thermal, acoustic, visual and air quality comfort variables and acceptability of the indoor conditions will be conducted. And a correlational study of the measured indoor environmental quality parameters and acceptability to determine comfort ranges for each of the components of IEQ.

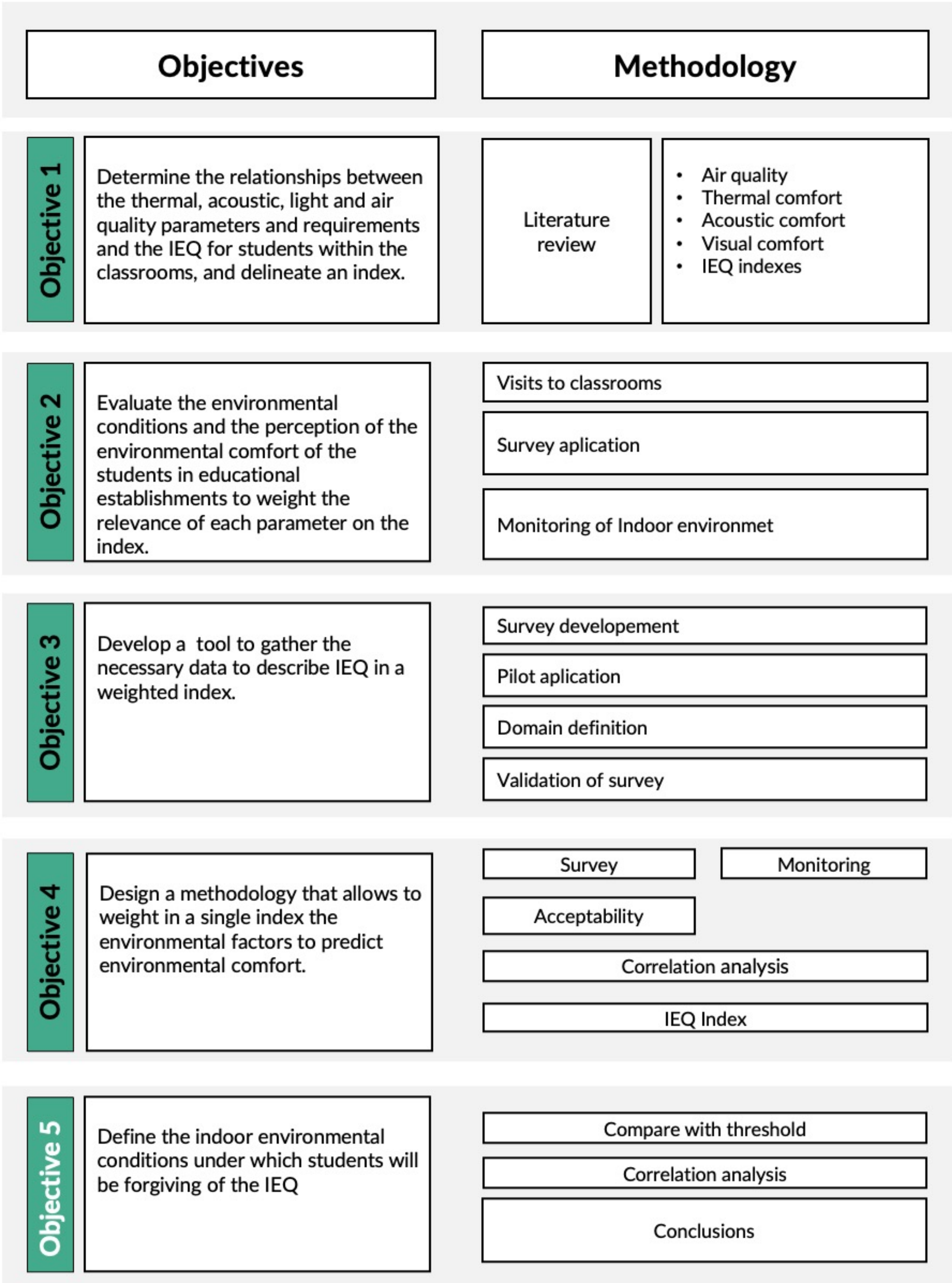


***Figure 3.1**: Research methodologies used in the PhD research and their corresponding tools.*

3.4 Sample selection

As explained in 3.2 Contextual limitations, the application of the survey was the most affected part of the dissertation due to the COVID-19 pandemic. Therefore, it was decided to work with secondary data for the first stages of the study. In this subchapter, each of the datasets will be described in terms of quality and quantity of data. The dataset used in Chapter 4, originated in a thermal comfort study in classrooms in Chile. This dataset was selected because it had the same unit of analysis (classroom) as the proposed research. At the same time, the quality of the measured data, in terms of measurement equipment end protocols was considered. The dataset was selected due to the quantity of data points, climatic variability of the schools measured and because it contained data from two seasons.

The second dataset selected was smaller in scope, only consisting of 12 classrooms in 6 schools in one city. This secondary datasets had the advantage of containing measurements of CO_2 concentration, temperature, humidity, and acoustic performance of the spaces. It also contained survey response that evaluated the four aspects of IEQ.

3.4.1 Socio-Environmental context

The socio-environmental context is a wide concept that will be used to define the climate and habitat in which the subjects of this study live. This context does not only comprise the climate but also the social conditions of subjects and could also determine their expectations and preferences for a comfortable environment. The context in this definition refers to the present time conditions, although it assumes that if a person changes their environment a period of acclimatization is needed.

In the context of this study, it is assumed that all students are acclimated to their socio-environmental context based on student retention informed by the school used in case studies. the period necessary for acclimatization is not clearly stated, Pierson (2019) cites Lysgaard 1955, that proposed a period of at least 25 months for cross-cultural adjustment. It is unclear the period needed for climatic adjustment.

The case studies in this research are all located in Chile. Considering the wide differences in climatic conditions along the country, a short explanation of each city's climatic condition will be presented. The cities are presented from north to south, where temperatures tend to drop to the south.

Santiago de Chile (33°27′S 70°40′ W)

Is the most densely populated city in Chile and concentrates half of the population. It has a Mediterranean climate with warm summer (Csb). The city is located in the foothills of the Andes. and has winter rains and a long dry season. The distance to the sea from the city accentuates the thermal oscillations, which are considerable daily and annually. The average temperature in summer is 20.1°C, with maximum averages over

29°C and minimum averages over 12°C, with maximum extremes of 34°C. In winter, the average temperature is 8.2°C, with average highs above 15°C and average lows close to 3°C, with extreme lows of−2°C. As a measure of heating and cooling demand. The city has 1093 Heating degree days (HDD) with a base temperature of 15.5°C and 160 cooling degree days (CDD) with a base temperature of 24°C (BizEE Software, 2021).

Puerto Montt (41°28′S 72°56′ W)

Is classified as MarineWest coast climate with warm summer (Cfb). The city is located directly on the coast of the protected northern end of the Reloncaví Estuary. The climate is characterized by abundant rainfall throughout the year, registering an average of 1800 mm per year, which does not define a dry season, despite decreasing considerably in summer. In winter, the average temperature is 6.5°C, with a maximum of 10.5°C and a minimum average of 3.9°C. In summer, the median temperature is 13.9°C, while the maximum average is 19.6°C and the minimum average is 9°C. The low thermal oscillation, both in the daily and annual regime, the extremely humid environment, and the cloudiness almost permanently define this climate. The city has 2007 HDD with a base temperature of 15.5°C and 3 CDD with a base temperature of 24°C (BizEE Software, 2021).

Concepción

The climate in this city is a Mediterranean climate with warm summer and oceanic influence (Csb') (Sarricolea et al., 2017). The dry season lasts about five to four months during summer. It is highly influenced by the proximity to the ocean, which moderates both daily and annual thermal oscillations. The annual variation of the average temperature is less than 8°C and its values are always moderate, averaging 15.9°C in summer and 9°C in winter. The average maximum temperatures recorded in summer are close to 22°C and slightly above 13°C in winter, while the average minimum temperature in the latter season is 6°C and 10.6°C in summer (Dirección General de Aeronáutica Civil, 2021). The city has 1183 HDDs with a base temperature of 15.5°C and 0 CDDs with a base temperature of 24°C (BizEE Software, 2021).

Coyhaique (45°34′S 72°4′W)

The city is located to the east of the Andes Mountains, in Chilean Patagonia at an average altitude of 310 meters above sea level, where the Simpson and Coyhaique rivers converge. Summers are humid and with maximum temperatures of up to 28°C, while in winter the temperature drops drastically. In winter temperatures drop to a minimum of -15°C. Precipitation is between 800 and 1200 mm per year, with abundant winter snow. The absolute minimum winter temperature reaches -26.4°C and the absolute maximum in summer is 35.7°C.

According to the Köppen classification (Sarricolea et al., 2017) the climate in this city is a Mediterranean climate with a mild summer (Csc). The city has 2694 HDD with a base temperature of 15.5°C and 14 CDD with a base temperature of 24°C (BizEE Software, 2021).

3.5 Data collection

For this research, primary and secondary data sources were used. Secondary sources were data from national and international authorities like census data and statistical data gathered by the Ministry of Education in Chile (MINEDUC). Other secondary sources like review articles, books, reports, and documents were also used. Other secondary data sources were existing datasets. While data collected for this research is defined as primary data. The following sections will describe the data collection tools and processes used to collect all datasets.

3.5.1 Indoor air quality (IAQ) in naturally ventilated primary schools in Chile

This secondary dataset was collected in 8 Primary schools located in urban areas across Chile during 3-4 consecutive days in two periods of time, representing winter and spring seasons. The classrooms were of similar size and housed between 26 and 45 students. The dataset was gathered by Trebilcock et al. (2017b) as part of Fondecyt research project N°1130596. The main researcher of the study made the data available for this study. A detailed description of the methodology and the dataset is given in Chapter 4.

Schools were all located in urban areas in Santiago de Chile and Puerto Montt. According to the normative, all the classrooms had natural ventilation through operable windows, and only cases located in Puerto Montt had heating systems. The occupancy period was from 9:00 to 15:45 in all classrooms, with two short breaks during the day and a break at lunchtime.

3.5.2 POE of classrooms in Coyhaique, Chile

This city in chilean Patagonia has a Mediterranean climate with a mild summer with 2694 HDD with a base temperature of 15.5°C. More details are presented in 3.4.1. The city has bad air quality related to heating with wood-burning stoves and low ventilation of the city due to its location between mountains and heat inversion (Perez et al., 2020). The city was ranked the 139th unhealthiest city in the world by a 2018 study by WHO. The POE was done by CITEC-UBB (Centro de Investigación en Tecnólogas de la Construcción) in 2019 aiming at proposing cleaner means of heating and evaluating retrofitting of the schools. The study was done on six different schools, and two classrooms in each. The dataset was made available for this study by CITEC-UBB. The report of the data cannot identify the schools, although the information was made available to the researcher. This dataset contains detailed architectural descriptions of the classrooms, measurements of T_a, HR and CO_2 as well as Survey responses. The survey used in this research is an expanded version of the one used in 3.5.1, which also includes questions about noise, ventilation, and lighting. The questionnaire is presented in ***Annex** 1* in English translation.

3.5.3 Survey validation

The survey (3.6 Survey development) validation was done in July and August 2021 after schools reopened in June 2021. Some constraints due to COVID-19 remained like low attendance (between 0 to 6 students per classroom) use of masks and overventilation of the classrooms. The development and validation of the survey will be further presented in Chapter 6. The methodology for this part of the study is described in Figure 3.2.

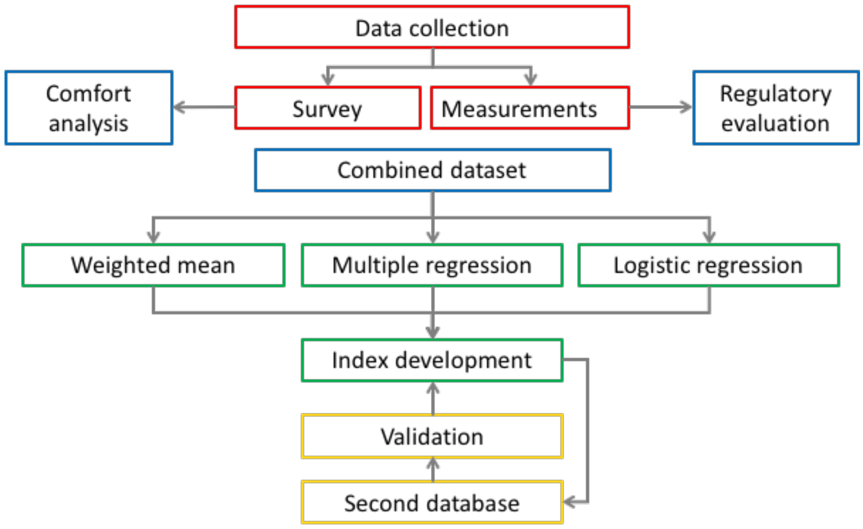


Figure 3.2: *Study conceptual framework for the development and validation of a survey to evaluate IEQ in schools.*

3.6 Survey development

The survey was developed to identify the Forgiveness of school children inside their classrooms, therefore their thermal, acoustic, visual, and air quality comfort was measured as well as their adaptation and forgiveness. The children were between 10 and 16 years old, studying in semi-public schools.

The age and development of children arose the need for a language adaptation of existing questionnaires, changing word use and explaining difficult concepts. A group of teachers of the same level of education participated in the linguistic validation of the survey.

For this step of the research, the possibility to correlate the indoor environmental comfort of school children through statistical analysis is of utmost relevance.

The first version of the survey was developed based on the nine domains previously defined. The questions were developed to assess the satisfaction of students with their classrooms to find a relation between the indoor environmental conditions and their indoor environmental comfort as a whole. Therefore, the survey will be conducted at the same time as measurements of IEQ are made.

Each domain of the survey contained between 3 and 5 items scored on a Likert scale. The 5-level scale was selected as a way to adapt to the age and development of children. The vocabulary was adapted to this scale going from very much to very little, instead of too much to too little.

Table 3.1: *initial domains and assessment items of the survey*

Domain	***Item number and description***	***Domain***	***Item number and description***
Personal Data	(1) Gender, Age, Working Years, use of glasses, feeling.	Visual Comfort	(19) Perceived lighting pleasantness
Indoor Environmental comfort	(2) Preference of temperature		(20) Perceived lighting
	(3) Preference of lighting		(21) Perceived reflections
	(4) Preference of acoustics		(22) View quality
	(5) Preference of air quality	Spatial configuration	(23) Perceived spatial configuration pleasantness
	(6) General satisfaction		(24) Perceived colours
Thermal Comfort	(7) Perceived temperature		(25) Perceived decoration
	(8) Perceived change during the day	Adaptation	(26) Adaptation to temperature
Air Quality	(9) Perceived quality		(27) Adaptation to air quality
	(10) Perceived dryness		(28) Adaptation to acoustic
	(11) Perceived human smell		(29) Adaptation to lighting
	(12) Perceived food smell	Forgiveness	(30) Relevance of temperature winter
	(13) Other types of smell		(31) Relevance of temperature summer
Acoustic Comfort	(14) Perceived acoustics pleasantness		(32) Relevance of air quality
	(15) Perceived noise		(33) Relevance of acoustics
	(16) Perceived noise inside		(34) Relevance of lighting
	(17) Perceived noise outside		
	(18) Perceived noise exterior		

With the aim to limit the questions made to the children, the information regarding location and closeness to the windows, clothing and time spent in the room were gathered directly by the researcher. These questions were included in a Building characterization checklist (BCC) that also includes other relevant information about the building as geometry, location, and climatic conditions on the day of the survey.

Based on the rule of thumb used in factor analysis (Book, 2013) saying that five respondents per question in a survey are enough to establish the sample size, a minimum sample size of 170 was established.

The survey was developed to be answered by pupils of public schools studying in elementary schools in Chile where surveyed aged between 10 and 13 Table 3.2. Therefore, directives of X elementary schools in the city of Concepción (Lat: -36.8271°, Long: -73.0503°), Chile were contacted. The selection of the classrooms was done for convenience, seeking to give uniformity to students in terms of origin, socio-economic level and level of study, and also uniformity to the classrooms under study, considering orientation, shape, percentage of windows and material of building. From the available classrooms, 7 classrooms (an average of 25 students) were selected.

***Table 3.2**: Primary school levels in Chile and age of students*

Primary school level	*age*
1st	6-7
2nd	7-8
3rd	8-9
4th	9-10
5th	10-11
6th	11-12
7th	12-13
8th	13-14

Respondents were surveyed inside their most used classroom during a typical class day at the end of summer. The surveys were handled on paper by the researchers in a two pages booklet structured into the beforehand defined domains (Table 3.1). Before starting the survey, it was read aloud and questions regarding vocabulary or concepts were answered by the researcher in a straightforward way. Students were instructed to raise their hand in case they don't understand a question while answering it. The time taken to respond to the whole survey was recorded for each of the surveys to then evaluate it in the quality assurance face. 14 days after completing the survey a second round of surveys was conducted with the same students. Each of them was given an Identity number (ID) to allow the comparison of both measurements to evaluate retest reliability.

The responses to the survey were tested to determine the items that should remain and the domain definition.

3.7 Building characterization checklist

Based on the literature review of POE, the need for a Building characterization checklist arose. A protocol to gather information about the space configuration of the classrooms under study was developed. The variables considered in this study are defined in 3.8.2 .

To simplify the survey for children's development at 10 years old, some questions related to clothing and location in the classroom were moved to the BCC, as explained in the previous section. This meant that the BCC needs to be completed every time the children are surveyed.

The BCC was developed with eight domains as presented in Table 3.1.

Table 3.3: *initial domains and assessment items of the BCC*

Domain	*Item number and description*
Classroom identification	Date, time, class group, room number, floor level, class level, teacher in room
Geometry of the building	Approximate size of room: length, width, ceiling height, windowsill, percentage of windows.
Weather conditions	Outdoor Temperature, season, Outdoor weather.
Lighting	Window orientation Window solar protection, percentage in use. Lighting fixtures type Lighting in use
Air Quality	Percentage of open windows Ventilation system in place Ventilation On-off
Equipment being used	Air temperature, radiant temperature, air movement, CO_2 meter, sonometer, particle matter, lux meter, HDR photography
Occupation	Number of students in class Previous class of students Location of students in the classroom
Clothing insulation	The outermost layer of clothing used by student

After the pilot application of the BCC, some minor changes were made to the structure, proposing the use of domains. And to the layout, to ease filling it on site. The final version of the BCC is presented in ***Annex** 2*. in its original language (Spanish) and an English translation.

3.8 Variables

It is fundamental, for any research to clearly define the variables under study. This research defines the following variables, to answer the main question proposed in this study *"What are the relationships between the thermal, acoustic, light and air quality conditions and requirements and the perception of IEQ from the perspective of school students in Chile?"*. For clarity, they will be presented based on their source. First measured environmental conditions in *3.8.1* and then variables related to perception and preference in 3.8.2.

3.8.1 Variables of the environmental conditions

The physical variables measured for this research were defined to represent the environmental conditions inside the classrooms. The data corresponding to the time of the survey will be correlated with children's perception of IEQ.

For the thermal indoor environment, the variables were selected based on the thermal comfort theory as proposed by Nicol, Humphreys and Roaf (2012, Chapter 8). The measurements were done according to the standardized protocols defined in EN15251 (Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings-Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, 2007).

According to EN15251, it is possible to evaluate air quality by measuring the average CO_2 concentration in the buildings as long as the main pollution source is the occupants. As it was stated by Chatzidiankou et al. (2015a), CO_2 concentration is a good proxy for IAQ in classrooms and represents ventilation effectiveness.

Lighting levels were measured on the work plane using illuminance as an indicator. The spot measurements were made every minute on the students' table.

Lastly, acoustic quality was evaluated using background noise as an indicator. The measurements were taken every minute with a sonometer.

***Table 3.4**: Variables, data type and unit.*

Aspect	*Variable*	*Type*	*Data type*	*unit*
Temperature	Air Temperature (T_a)	measurement	Ordinal – continuous	°C
Temperature	Radiant Temperature (T_r)	measurement	Ordinal – continuous	°C
Temperature	Air velocity (v)	measurement	Ordinal – continuous	m/s
Temperature	Relative humidity (HR)	measurement	Ordinal – continuous	%
Air quality	CO_2 concentration	measurement	Ordinal – continuous	ppm
Air quality	Relative humidity (HR)	measurement	Ordinal – continuous	%
Lighting conditions	illuminance	measurement	Ordinal – continuous	lux
Acoustics	background noise	measurement	Ordinal – continuous	Leq

3.8.2 Variables related to space configuration

The special layout of the classroom is relevant to IEQ and the evaluation of IEQ of the children.

Table **3.5** presents the variables used in this study, the aspect that they are related to, the data type and the units of measurement. Variables related to space use are described in Table 3.6, and the variables of perception and preference in Table 3.7. Lastly, variables that characterize the personal information of the occupants are described in Table 3.8.

Table 3.5: *variables related to space configuration*

Aspect	*Variable*	*Type*	*Data type*	*unit*
Temperature	Availability of heating system	observation	Categorical	yes/no
Temperature	Availability of cooling system	observation	Categorical	yes/no
Air quality	Availability of mechanical ventilation system	observation	Categorical	yes/no
Air quality	Size of operable windows	measurement	Ordinal – continuous	m^2
Air quality	type of window opening	observation	interval	0% 1-20% 21-30% 50-60% 60% or more
Lighting conditions	Window orientation	measurement	interval	N NE NW S SE SW E W
Lighting conditions	window-to-floor area ratio (Catalina & Iordache, 2012)	measurement	Ordinal – continuous	%
Acoustics	acoustic treatment of walls	Presence of acoustic elements	Categorical	yes/no
	acoustic treatment of floor		Categorical	yes/no
	acoustic treatment of the ceiling		Categorical	yes/no

Table 3.6: *variables related to space use*

Aspect	*Variable*	*Definition*	*Type*	*Data type*	*unit*
Temperature	Use of the heating system	the system is operating at the time of the survey	observation	Categorical	yes/no
Temperature	Use of the cooling system	the system is operating at the time of the survey	observation	Categorical	yes/no
Air quality	Occupant density	number of students in the classroom related to the floor area of the space	observation	Ordinal – continuous	m^2/ person
Air quality	Occupant density	number of students in the classroom related to the air volume of the space	observation	Ordinal – continuous	m^3/ person
Air quality	Open windows	percentage of the total area of glazing that is open at the time of the survey	observation	interval	0% 1-20% 21-30% 50-60% 60% or more
Air quality	Open door	if the door is open or closed at the time of the survey	observation	Categorical	yes/no
Lighting conditions	Type of curtains	material and colour	observation		
Lighting conditions	use of curtains	percentage of windows covered by curtains	observation	Ordinal – continuous	%
Lighting conditions	Teaching method	The methodology of teaching used at the time of the survey will define the amount of light needed.	observation	Categorical	reading listening presentation whiteboard group work
Acoustics	Teaching method	The methodology of teaching used at the time of the survey will define the type of noise produced inside the classroom	observation	Categorical	teacher speaking focus work students speaking group work

Table 3.7: *Variables of perception and preference*

Aspect	*Variable*	*Type*	*Data type*	*unit*
Preference	Preference of temperature	Survey questions with 5 categories	categorical	Much Cooler, Cooler, Same, Warmer, Warmer, much Warmer
Preference	Preference for air quality	Survey questions with 5 categories	categorical	more ventilation, a little bit more ventilation, same, a little bit less ventilation, less ventilation
Preference	Preference of acoustics	Survey questions with 5 categories	categorical	more noise, a little bit more noise, same, a little bit less noise, less noise
Preference	Preference of lighting	Survey questions with 5 categories	categorical	more natural light, a little bit more natural light, same, a little bit less natural light, less natural light
Indoor Environmental comfort	General satisfaction	Survey questions with 5 categories	categorical	very bad, bad, not good or bad, good, very good
Thermal Comfort	Perceived temperature	Survey questions with 5 categories	categorical	Very unpleasant, unpleasant, Neither good nor bad, pleasant, very pleasant.
Thermal Comfort	Perceived change during the day	Survey questions with 5 categories	categorical	Very changeable, Changeable, Pleasant, Stable, Very stable.
Air Quality	Perceived quality	Survey questions with 5 categories	categorical	Very unpleasant, unpleasant, Neither good nor bad, pleasant, very pleasant.
Air Quality	Perceived air dryness	Survey questions with 5 categories	categorical	Very humid, Humid, Neither good nor bad, Dry, very dry.
Air Quality	Perceived human smell	Survey questions with 5 categories	categorical	Strong odour, Odour, Neither good nor bad, Low odour, No odour
Air Quality	Perceived food smell	Survey questions with 5 categories	categorical	Strong odour, Odour, Neither good nor bad, Low odour, No odour
Air Quality	Other types of smell	Survey open question	categorical	--
Acoustic Comfort	Perceived acoustics pleasantness	Survey questions with 5 categories	categorical	Very unpleasant, unpleasant, Neither good nor bad, pleasant, very pleasant.

Acoustic Comfort	Perceived noise	Survey questions with 5 categories	categorical	Very noisy, Noisy, Neither good nor bad, No noise, No noise at all
Acoustic Comfort	Perceived indoor noise	Survey questions with 5 categories	categorical	Very noisy, Noisy, Neither good nor bad, No noise, No noise at all
Acoustic Comfort	Perceived outdoor noise	Survey questions with 5 categories	categorical	Very noisy, Noisy, Neither good nor bad, No noise, No noise at all
Visual Comfort	Perceived lighting pleasantness	Survequestionson with 5 categories	categorical	Very unpleasant, unpleasant, Neither good nor bad, pleasant, very pleasant.
Visual Comfort	Perceived lighting	Survequestionson with 5 categories	categorical	Too little, little, neither good nor bad, a lot, too much.
Visual Comfort	Perceived reflections (glare)	Survey question	categorical	yes, no
Visual Comfort	VieQualityty	Survequestionson with three categories	categorical	yes, no, I don't see why the curtain is closed.

Table 3.8: *Variables related to personal data*

Aspect	*Variable*	*Definition*	*Type*	*Data type*	*unit*
Personal	age	age at the time of the survey	Survey question	ordinal	years
Personal	gender		Survey question	nominal	female, male
Personal	use of glasses		Survey question	nominal	yes, no
Personal	general feeling	the general feeling on the date y of the survey	Survey questions with 5 emoji categories	categorical	
Personal	Clo	level of insulation of clothing at the time of the survey	calculated on observation	ordinal	0,75 clo 1 clo 1,2 clo
Personal	school level	the level that the respondent is currently attending.	Survey question	ordinal	5^{th}, 6^{th}, 7^{th}, 8^{th}.

3.9 Data management

Surveys were collected in paper format, as described in 3.6. The database was developed in Excel presenting the data in an orderly and logical way. Each question was coded, and each school, classroom and student were given a code to identify them. The date and time of the survey were also translated into the ISO format to make it possible to then compare with measured data.

3.9.1 Anonymization

To protect the anonymity of the people involved in this study, codes were assigned to each school and classroom and each student. Following the code developed for paper 1 (Diaz, Cools, et al., 2021) the code included 3 letters for the city, two numbers for the school and one number for the classroom. Students received a randomized three digits ID. Since each student answered more than one time the survey, the ID was assigned to each one of the students.

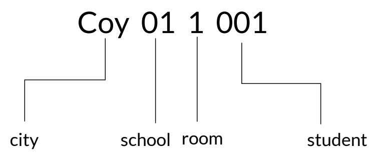


Figure 3.3: *ID format for anonymization of survey data*

3.9.2 Data Cleansing

The data cleansing process was done to remove the surveys that did not allow to answer the research question or that had contradictory responses. This process is relevant because when analysing the whole dataset, it is difficult to identify these errors. Three rules were used to prevent internal consistency problems and ensure the quality of the data:

Rule 1: straight-liners

The first rule to ensure data quality is to exclude straight-liners. This is when rogue respondents select the same answer in almost any question, to speed the process or to not give their honest opinion.

Rule 2: incomplete survey

Incomplete surveys could mean that the respondent did not understand or did not have a clear answer to a question. On the other hand, it could mean that the respondent is not interested in answering the survey or does not want to express their opinion. As long as the key questions were answered (for example both thermal perception vote and thermal preference vote) the surveys were included in the study.

Rule 3: incongruent answers

This rule is applied to each domain and is topic sensitive. Each rule will be explained in detail in the section dealing with the development of the index (chapter 7). As a general rule, questions will be paired, and unacceptable answers were defined. For example, if the thermal perception vote is “cold” an unacceptable answer for the thermal preference vote would be “much colder”.

3.10 Statistical methods

To define the statistical analysis to use, the type of data should be clearly stated. In general, data can be classified as categorical, ordinal and interval. Categorical data cannot be ordered. Examples in the survey are the use of glasses or sex. Ordinal data refers to data that can be transformed into a scale such as Likert. Lastly, interval data are continuous and numerical. There are no interval data in the survey, but all measured data is interval, for example, Air Temperature (Ta) measured in Celsius and Air velocity (v) measured in m/s.

To define the tests that can be applied to the dataset, the distribution, normality, and scale of the data need to be addressed. Once this is addressed, we can decide if parametric or non-parametric tests can be used (A. Field & Iles, 2016).

The normality of the data is usually evaluated using a graphical representation of the data called a histogram. Other ways of evaluating normality are Kolmogorov-Smirnov or Shapiro-Wilks tests and QQ plots. Histograms that represent normality will be bell-shaped, meaning that the data points are symmetrically distributed from the peak in the middle. The normal distribution is often called a Gaussian distribution (Heumann et al., 2016).

3.10.1 Spearman’s Rank Correlation

This technique organized variables into ranks and then looks at the correlation between two sets of ranks. This means that the correlation coefficient uses only the ranks of the values and not the values themselves. Through this transformation, we can evaluate and compare ordinal and continuous variables. For the interpretation of this correlation, it is relevant to note that the resulting values will lie between -1 and +1. When the observations are given exactly the same rank, then the resulting value will be 1, if they are assigned exactly the opposite rank, the resulting value will be -1. In both cases, we will see a strong correlation, in the first case a positive and in the second case a negative correlation. When the resulting coefficient approaches 0, it indicates that there is no found correlation. Even if the correlation coefficient is zero, a non-linear relationship might exist.

Another correlation coefficient commonly used is Pearson's. This coefficient will only reflect linear correlations and can only be applied to "either two continuous or two ordinal variables or a combination of an ordinal and a continuous variable, but not for two nominal variables" (Heumann et al., 2016, Chapter 4.3.3). Pearson's coefficient used the entire information contained in the continuous data, whereas Spearman's only uses the ordinal information.

To evaluate the correlation coefficients (for both Spearman's and Pearson's), thresholds differ between authors and research areas. In his review paper, Akoglu (2018) presents a table of interpretation of coefficients. An extract from this table is presented in Table 3.9. For this research, the interpretation of Chan (2003) will be used.

Table 3.9: *Interpretation of Pearson's and Spearman's coefficients. Based on Table 1 by Akoglu,* (2018)

Correlation coefficient	*Psychology (Dancey & Reidy, 2007)*	*Medicine (Chan, 2003)*
+- 1	Perfect	Perfect
+- 0.9	Strong	Very strong
+- 0.8	Strong	Very strong
+- 0.7	Strong	Moderate
+- 0.6	Moderate	Moderate
+- 0.5	Moderate	Fair
+-0.4	Moderate	Fair
+- 0.3	Weak	Poor
+- 0.2	Weak	Poor
+- 0.1	Weak	None
0	Zero	None

Spearman's coefficient will be used in this study to explore correlations between measured variables (ex. T_r and HR) or to explore correlations between perception and measured data (ex. TSV and T_r).

3.10.2 Binary Logistic Regression Analysis (BLR)

This technique can be applied when the dependent variable is categorical or has been turned into a categorical dichotomous[10] variable, where both categories are mutually excluded. For example, in *Paper 1,* the measured interval data for CO2 concentration (in ppm) was transformed to a categorical variable that stated that the measure was an "acceptable CO_2 concentration "according to EN 13779:2007(EN 13779: Ventilation for Non- Residential Buildings – Performance Requirements for Ventilation and Room-Conditioning Systems, 2007). When using this technique, it is possible to evaluate the impact of multiple independent variables that are present simultaneously on the dependent variable.

- The results of BLR are in the form of an odd ratio. This means the probability of membership in the defined category.
- BLR determines the impact of multiple independent variables presented simultaneously.
- Logistic regression does not assume a linear relationship between the dependent and independent variables, but a linearity of independent variables.
- The sample size is generally greater than for linear regression. Depending on the authors, a minimum sample of 10 observations per independent variable in the model is suggested (Hosmer et al., 2013).

3.11 Informed consent and ethics committee

All procedures and instruments presented in this dissertation were approved by the ethics committee of the Universidad del Bio-Bio. All participating occupants signed an informed consent form that was presented to them at the beginning of their participation as a prerequisite for participation

3.12 Conclusions

This chapter presents the methodological framework defined for this research. This framework positions itself in the state of the art and complies with the ethical requirements for surveying people and working with humans.

[10] 2 categories

4 Effect of environmental factors on the concentration of CO_2

This chapter presents an exploration on the effects that environmental factors, as well as climatic conditions and season have on the concentration of CO2 in school classrooms.

This research was developed with the aim of partially answering research question 1 of this research.

1. *What are the relationships between the thermal, acoustic, light and air quality conditions and requirements and the perception if IEQ from the perspective of school students in Chile?*
2. *What is the perception of the environmental comfort of the students in their classrooms?*
3. *What is the relevance given by students to each parameter of IEQ?*
4. *Under which conditions will students be forgiving of the IEQ?*

The main results of this research show that season has an impact on thermal and air quality environment. The different cities present unique constrains to ensure good air quality. When the indoor air is hot, the adaptative response is to open windows to lower the temperature, this strategy also lowers CO_2 concentration, meaning that air quality improves. During the winter, the need to conserve heat diminishes ventilation, promoting CO_2 concentration build-up. Finally, indoor temperature is a relevant factor in predicting CO_2 concentrations.

Part of the results of this Chapter were presented in paper 1: '*Effects of Climatic Conditions, Season and Environmental Factors on CO2 Concentrations in Naturally Ventilated Primary Schools in Chile*' (Diaz, Cools, et al., 2021).

4.1 Introduction

School classrooms are the indoor spaces where children spend most of the time, other than their homes. According to the 2019 report from Organization for Economic Co-operation and Development (OECD), the compulsory instruction time is between 7360 and 2393 h per year in primary education (David & Amey, 2020), and most of those hours are spent inside a classroom. These spaces are characterized by high occupant density and low air volume per student (Batterman et al., 2017). The time spent indoors is mostly in the same classroom, with predefined breaks where they leave the room. At the same time, children, in a traditional classroom, have reduced mobility and, therefore, limited options to adapt or modify their surroundings (Haddad et al., 2017; Wargocki & Wyon, 2013).. Indeed, most of the adaptative actions are performed by the teachers, based on their own comfort or requests made by the children (Zhang & Bluyssen, 2019). All these factors make it more challenging to provide good indoor air quality (IAQ) in classrooms than other buildings.

The lack of proper indoor air quality is related to asthma, allergies, and other illnesses, sometimes referred to as sick building syndrome (SBS). It is also relevant to note that children are more susceptible to long-term health damage due to low indoor environmental quality (IEQ) (Chithra & Shiva Nagendra, 2018; Faustman et al., 2000; Haverinen-Shaughnessy et al., 2015; Yassin & Pillai, 2019).

Indoor air quality will be affected by various contaminants that can be produced inside or outside the building. Indoor pollutants can have a human origin, like CO_2 from respiration and odours, or be emitted by the building materials. Other indoor contaminants are released by cleaning agents and products used in educational activities (Lucialli et al., 2020).. Outdoor sources of pollutants are related to productive activities performed in the school's vicinity, roads' proximity, and local climatic conditions (Becerra et al., 2020).

A common classification scheme of contaminants is based on their origin. Biological pollutants are mould; endotoxins; bacteria; viruses; and allergens, like dust mites, pet hair, or pollen. Chemical pollutants include organic and inorganic gasses, such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO, NO_2), and ozone (O_3), among others. Volatile organic compounds (COVs) are also classified as chemical compounds. Most of the COVs are originated from construction materials, furniture, and cleaning products in school classrooms. The chemical contaminants with the highest presence in classrooms are benzene, toluene, xylene, ethylbenzene, α-pinene, and d-limonene (Chatzidiakou et al., 2014; de Gennaro et al., 2013; Geiss et al., 2011; Madureira et al., 2015; Safar et al., 2019; Yassin & Pillai, 2019). The last category is physical pollutants; a common denomination for dust particles is between 0.01–200 μm. Metals can also be classified as physical pollutants when they are present as particles between 0.1 and 30 μm.

Previous research conducted by Chatzidiakou et al. (2015a, 2015b) found that CO_2 can be used as a proxy for indoor air quality in classrooms, considering that low CO_2 concentration is correlated with the dilution of indoor pollutants and the purge of airborne particles. It is relevant to note that, although a correlation between CO_2 concentration and cognitive performance has been found (Du et al., 2020), it is not clear that CO_2 concentration is the cause of the decline in performance (Mishra et al., 2020); therefore, CO_2 is considered a proxy for indoor air quality (ANSI/ASHRAE Standard 62.1-2022 Ventilation for Acceptable Indoor Air Quality, 2022; Chatzidiakou et al., 2015a, 2015b; Education & Skills Funding Agency, 2018; Shendell et al., 2004; Wargocki et al., 2020a), not as a contaminant.

In school classrooms, the lack of IAQ can lead, directly or indirectly, to health problems, low productivity (Bakó-Biró et al., 2012; Tahsildoost & Zomorodian, 2018a), and absence (Chatzidiakou et al., 2012; Daisey et al., 2003; M. J. Mendell & Heath, 2005; Salleh et al., 2011; Wargocki & Wyon, 2013). Studies conducted in schools in Washington and Idaho (Shendell et al., 2004) found a correlation between high concentrations of CO_2 and lower attendance. This correlation was further studied for California primary schools (M. J. Mendell et al., 2013) and found that increasing the ventilation rates by 1 L/s per person could increase attendance while positively affecting learning outcomes. Haverinen-Shaughnessy and others (Haverinen-Shaughnessy et al., 2011b) found that IAQ is related to cognitive function and productivity and that increasing the ventilation rates in classrooms should improve the students′ academic achievement. This claim was confirmed by Toftum et al. (Toftum et al., 2015) in a study conducted in Danish Schools. Wargocki et al. (Wargocki et al., 2020a) present a review of the effects that indoor air quality in classrooms has on students′ performance and health. In this study, researchers were able to find a relationship between CO_2 concentration and ventilation rates and learning outcomes, concluding that reducing CO_2 concentrations from 2100 to 900 ppm would increase the performance speed by 12% and accuracy by 2%, while also improving the performance of national tests and school-leaving examinations by 5%. Considering attendance as an indicator of health, they concluded that reducing CO_2 from 4200 ppm to 1000 ppm would increase children′s daily attendance by 2.5%. Although the results presented do not apply to every classroom, we can assume that improved performance and health can be expected when indoor air quality is improved.

In naturally ventilated classrooms, this issue is more relevant than in mechanically ventilated ones (Gao et al., 2014). Indoor air quality has been related to outdoor conditions, including the location of the school (urban or rural) and climatic conditions (wind speed and direction, outdoor temperatures), as well as window opening behaviour and willingness of pupils and teachers to open windows (Wargocki & Da Silva, 2015). Korsavi et al. (2020a) suggest that some factors related to IAQ are occupants' adaptive behaviour, occupancy patterns, CO_2 generation rates, and occupant density and highlight the potential of the classrooms to facilitate adaptative behaviours. Based on studying a sample of 29 naturally-ventilated classrooms in the UK during non-heating and heating seasons, they proposed a classification of the main factors affecting ventilation rates, and, therefore, IAQ sorting them into three groups: contextual, occupant-related, and building-related (COB) factors (Korsavi et al., 2020e).

Although some studies have been done on indoor air quality in Chilean schools since 2011 (Armijo et al., 2011; M. Piderit et al., 2019; Rivera & Kwok, 2019; Trebilcock et al., 2012), the lack of statistical analysis made it impossible to identify the cofounding factors that affect the IAQ in the context of naturally ventilated schools in a non-industrialized country.

4.1.1 Aim and Contribution of this Study

Considering the proven negative effects that poor air quality in classrooms has on the health and performance of children, this paper's main objectives are as follows:

1. Evaluate CO_2 concentrations in naturally ventilated classrooms and compare them with thresholds.
2. Identify the cofounding factors that will lead to acceptable CO_2 levels, according to EN 13779:2007 (EN 13779: Ventilation for Non- Residential Buildings – Performance Requirements for Ventilation and Room- Conditioning Systems, 2007) and EN16798-3 (EN 16798-3 : Energy Performance of Buildings - Ventilation for Buildings - Part 3: For Non-Residential Buildings - Performance Requirements for Ventilation and Room-Conditioning Systems, n.d.) in naturally ventilated school classrooms under normal occupation conditions.
3. Propose strategies to improve IAQ through design.

One of the hypotheses being tested is that the need to conserve heat prevents ventilation in the cold season, having a detrimental impact on air quality. The results of this research can be valuable to building managers and designers of retrofitting strategies, mostly at the government level. The originality of this research is performing a binary logistic analysis to identify the factors that define acceptable CO_2 concentrations. Considering that the variables under study (CO_2 concentration and temperature and humidity) are continuous variables, and Binary Logistic Regression (BLR) was used instead of ANOVA.

This paper's organization is as follows: Section 2 is devoted to the Materials and Methods, which describes the definition of variables under study and data collection. It also describes the data processing and the statistical analysis of the IEQ conditions in the classrooms that would predict IAQ. Section 3 presents the monitoring phase results and the results of the statistical analyses performed to make the association between classroom IEQ and IAQ. Section 4 discusses the findings and the limitations of the study. Section 5 presents the conclusions from this research.

4.2 Materials and Methods

This paper aims to investigate the cofounding factors that will lead to acceptable CO_2 levels in naturally ventilated school classrooms under normal occupation conditions, considering the local architectural design, materials, and systems, as well as climatic and cultural conditions. The research methodology was defined based on a literature review of similar studies and is organized in steps, as presented in the conceptual framework in **Figure 4.1**: (1) Definition of research design. (2) Sample selection. (3) Data acquisition. (4) Evaluation of CO_2 concentration against thresholds. (5) Regression analysis and quality assurance.

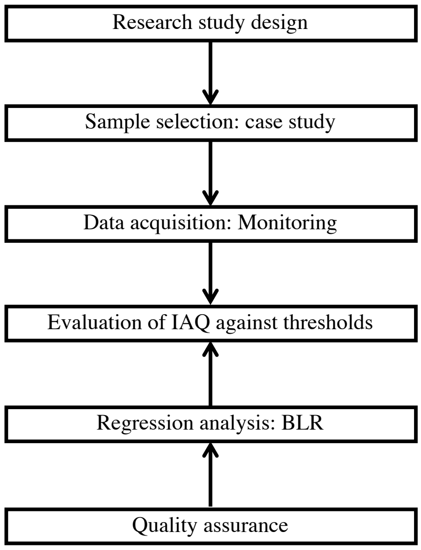


Figure 4.1: *Study conceptual framework.*

4.2.1 Study Variables and Selection of Cases

In this study, the dependent variable will be CO_2 concentration as a proxy for IAQ. In contrast, the independent variables were defined, based on the characterization made by Korsavi (2020e) and the literature review. The factors under study are contextual factors: season, operative temperature (Attia et al., 2019; Teli et al., 2013; Trebilcock et al., 2017a), outside temperature, and humidity; building-related factors: room's volume and dimensions; and occupant-related factors: occupant density (Korsavi et al., 2020a)

It is noteworthy that the required threshold for classrooms' indoor environmental quality (IEQ) in Chile is limited to temperatures above 12 °C in classrooms (Decreto

548, 2012), while no requirement is made for IAQ. The only related constraint is a defined percentage of glazing according to latitude, without clarifying if the windows need to be open or not. Occupant density in classrooms must be less than 1.1 m^2/student, and the minimum volume of air is 3 m^3/student, and the minimum height of the rooms is set at 2.2 m (Ministerio de Vivienda y Urbanismo, 2014). Several standards and certification schemes suggest other requirements for the indoor environmental quality of school classrooms, but they are nonmandatory and are mainly applicable to new buildings (Citec UBB & Decon UC, 2011; Instituto de la Construcción, 2014)

The selection of cases had to consider that the school system in Chile categorizes schools based on ownership and type of administration as public, subsidized, and private. It is assumed that the maintenance and operation founding defer between these three categories. This study focuses only on public and subsidized schools, as they are founded and regulated by the Ministry of Education. The criteria for selecting cases were based on availability, and the unit of analysis is defined at the classroom level.

Climate

Considering the diversity of climates in Chile, this study is focused only on two different climatic conditions, each represented in one city. The aim of selecting these two cities is to understand differences between climatic conditions and validate the potential for natural ventilation for air quality in each city and confirm if outdoor conditions affect indoor IAQ (Gao et al., 2014). Both cities have clear differences between seasons and each other. Based on the updated Köppen–Geiger climate classification for continental Chile (Sarricolea et al., 2017), Santiago de Chile (33°27′00″ S 70°40′00″ O) has a Mediterranean climate with warm summer (Csb). The city is located in the foothills of the Andes. It has winter rains and a long dry season. The distance to the sea from the city accentuates the thermal oscillations, which are considered daily and annually. The average temperature in summer is 20.1 °C, with maximum averages over 29 °C and minimum averages over 12 °C, with maximum extremes of 34 °C. In winter, the average temperature is 8.2 °C, with average highs above 15 °C and average lows close to 3 °C, with extreme lows of −2 °C.

On the other hand, Puerto Montt (41°28′18″ S 72°56′23″ O) is classified as Marine West coast climate with warm summer (Cfb). The city is located directly on the coast of the protected northern end of the Reloncaví Estuary. The climate is characterized by abundant rainfall throughout the year, registering an average of 1800 mm per year, which does not define a dry season, despite decreasing considerably in summer. In winter, the average temperature is 6.5 °C, with a maximum of 10.5 °C and a minimum average of 3.9 °C. In summer, the median temperature is 13.9 °C, while the maximum average is 19.6 °C, and the minimum average is 9 °C. The low thermal oscillation, both in the daily and annual regime, the extremely humid environment, and the cloudiness almost permanently define this climate. It is relevant to note that Santiago is the most densely populated city in Chile and concentrates half of the population, making it a relevant case study. On the other hand, Puerto Montt represents the south of the country, where winters are colder and rainy, while also being a regional capital.

Buildings

Most of the schools in Chile are naturally ventilated, and the installation of any form of heating systems is not required by normative; the only requirement is to maintain a temperature above 12 °C (Decreto 548, 2012, sec. Article 9) in primary and secondary schools from 36°38′12″ S to the south. Therefore, Santiago de Chile′s buildings did not include heating systems, while the ones in Puerto Montt had functioning heating systems. The regulation does not require cooling in summer in any part of the country. The selected schools are all public schools that receive funding through the municipal government or subsidized schools that receive funding through the municipal government and fees paid by the students' parents. The cases′ selection was made on the schools′ directors' availability and willingness to grant access to the researchers.

Data on building characterization was gathered through observation, checklists, and data provided by the Education Ministry. The collected information included microclimate (all the selected schools are urban), construction characteristics, maintenance and operation of school buildings, occupancy patterns, and socioeconomic data of the students. In Figure 2, pictures of the classrooms are presented: the top row shows the classrooms in Puerto Montt, and the bottom row shows the ones in Santiago.

Figure 4.2: *Classrooms under study*

Occupants

Among the primary school students, the 4th-year elementary class with students between 9 and 10 years old was selected, considering the balance between understanding the questionnaire and a longer permanence in the classroom than older children. The number of students at each school varied between 26 and 42 children per class, and their presence during monitoring further depended on school attendance. The attendance was recorded three times a day at 08:30, 11:30, and 15:00. Therefore, the four blocks of classes were assigned, as per **Table 4-1**. Breaks of 15 min were assigned, but the opening of windows during this period was not registered.

Table 4-1: *Schedule and time of the day that the attendance was recorded*

Teaching Schedule	*Attendance Log Time*
08:30–09:45	08:30
10:00–11:45	11:30
12:00–13:45	11:30
14:00–15:45	15:00

Monitoring

The methodology used for collecting data was the transverse method, collecting data in 8 primary schools located in urban areas across Chile during 3–4 consecutive days in two periods of time. The days selected were representative of that year's winter and spring seasons. Values for temperature, humidity, and solar radiation correspond to the typical values for those periods. The classrooms were of similar size (mean: 52,1 m^2) and housed between 26 and 42 students; see **Table 4-2**. It is important to note that the occupant density (according to the number of students enrolled) was between 1.1 and 1.9 m^2 per student, which complies with regulation but is far from international standards (Fisk, 2017). The schools were all located in urban areas; code SCL corresponds to Santiago de Chile, and PMC to Puerto Montt. According to the normative, all the classrooms had natural ventilation through operable windows, and only cases 5–8, located in Puerto Montt, had heating systems. The occupancy period was from 0900 to 1545 in all classrooms, with two short breaks during the day and a break at lunchtime.

Table 4-2: *Description of case studies*

	SCL 1	*SCL 2*	*SCL 3*	*SCL 4*	*PMC 1*	*PMC 2*	*PMC 3*	*PMC 4*
Number of students (n)	36	39	41	39	44	35	45	26
Classroom area (m2)	55.8	56.1	50.8	52.5	49.8	51.9	50.3	49.7
Occupant density (m2 /student)	1.6	1.4	1.2	1.3	1.1	1.5	1.1	1.9
Classroom volume (m3)	167.4	151.6	162.7	136.5	149.5	148.2	140.9	139.1
Total of winter working days monitored	4 days	3 days	3 days	3 days	4 days	4 days	4 days	4 days
Total of spring working days monitored	4 days	4 days	4 days	4 days	4 days	4 days	4 days	4 days

Environmental Measurements

Measurements were obtained using a Delta Ohm HD32.3 instrument that registered dry bulb temperature (Ta), globe temperature (Tg), relative humidity (RH), and air velocity (Va) at 5 min intervals during the occupied period (0900 to 1500) in all classrooms. CO_2 concentration was measured with Hobo Carbon Dioxide Logger at the same interval, considering it as a proxy for indoor air quality (ANSI/ASHRAE Standard 62.1-2022 Ventilation for Acceptable Indoor Air Quality, 2022; Chatzidiakou et al., 2015a, 2015b; Education & Skills Funding Agency, 2018; Shendell et al., 2004; Wargocki et al., 2020a), not as a contaminant. **Table 4-3** summarizes the characteristics of the equipment. As was described in a previous publication (Korsavi et al., 2020c; Mumovic et al., 2018; Trebilcock et al., 2017a), which used the same data collection protocol, teachers and students did not receive any recommendation regarding when to operate windows and did not have control over heating systems, if existing (only cases 5–8, corresponding to Puerto Montt, had a heating system).

Table 4-3: *Summary of the parameters, measurement intervals, and equipment characteristics.*

Monitored parameters	*Duration of measurement*	*Intervals*	*Measuring range*	*Accuracy*	*Equipment*
Globe temperature	3–4 school days	5 min.	−10 to 100 °C	±0,1 °C	Delta Ohm HD32.3
Relative humidity	Idem	Idem	5–98%	±2%	Idem
Carbon dioxide concentration	Idem	Idem	0 to 5000 ppm	±50 ppm	Hobo Carbon Dioxide Logger

Thresholds

Temperature is established as compliant when it is higher than 12 °C, as per Chilean standard (Decreto 548, 2012). For this study and based on the international requirements and the proposed new regulation for IEQ in schools in Chile (not published), temperatures between 18 °C and 25 °C are desirable. Considering that Chile does not have regulations regarding IAQ, the thresholds used are the categories defined in EN 13779:2007 (EN 13779: Ventilation for Non- Residential Buildings – Performance Requirements for Ventilation and Room- Conditioning Systems, 2007) for indoor CO_2 concentrations.

4.2.2 Statistical Analysis

Before studying the correlation between parameters, we present descriptive statistics. Considering that environmental factors are not normally distributed, mean, median, interquartile range, standard deviation, and maximum concentrations were used to describe each of the parameters of interest at the classroom level.

The collected data had a hierarchical structure (city, season, school, observations), where observations are dependent. Therefore, conventional single level statistical methods were not used.

A binary model using Binary Logistic Regression (BLR) was applied to explore the relationship between acceptable CO_2 concentrations (response variable) and contextual, occupant, and building (Korsavi et al., 2020e) factors (predictor variables), as shown in **Table 4-4**. The threshold values expressed in the table were taken from EN 13779:2007 for CO_2 concentrations, temperature, and humidity thresholds and were defined, based on the proposed new regulation for IEQ in schools in Chile (not published). This method is applicable when the predictor variables are ordinal variables that take only values that have a natural ordering and have more than two categories. The results of this analysis are odds ratios that describe the likelihood of having acceptable CO_2 concentrations when one of the predictor variables is increased by one unit. In contrast, the other variables are kept constant. The odds ratios were then used to rank the parameters regarding their importance for acceptable CO_2 concentrations. Binary Logistic Regression was calculated with SAS/STAT® software, and only the data for occupied periods were used. The Wald Chi-Square test tested the statistical significance of each predictor variable in the regression model.

Table 4-4: *Binary categories.*

Binary Category	*CO_2 Level*	*Indoor Temperature*	*Outdoor Temperature*	*Indoor RH*	*Outdoor RH*
Acceptable	CO_2 < 1000 ppm	18–24.9	18–24.9	30–50	30–50
Non-acceptable	1000 < CO_2	<18 or >25	<18 or >25	<30 or >65	<30 or >65

4.3 Results

4.3.1 Thermal Conditions

Indoor thermal conditions in the classrooms under the study varied between 9.9 °C and 20.1 °C in Santiago (no heating systems) and between 11 °C and 22.6 °C in Puerto Montt (with heating systems) during the occupancy period in winter. In spring, the temperature varied between 18.0 °C and 32.2 °C in Santiago, where cooling is not included in schools, and outside temperatures are high. In Puerto Montt, spring temperatures varied between 10.3 °C and 23.8 °C. More information about thermal perception and comfort for some of the Santiago cases is available in (Trebilcock et al., 2017a).

In winter, schools in Santiago have temperatures lower than 18 °C between 91.78% and 49.32% of the time, while classrooms in Puerto Montt, with a colder climate but compensated with heating systems, had temperatures lower than 18 °C between 0% and 55% of the time.

4.3.2 CO_2 Concentration

The statistical distributions of CO_2 ppm measurements for all cases in spring and winter are shown in **Figure 4.3**. The Figure displays medians below 1500 for all cases in spring, while in winter, most of them rise over this threshold (five of eight). Variability was also bigger in winter, where higher concentrations were observed. This suggests that natural ventilation through windows is being used primarily in spring, but only when the outside temperature is higher. It is not clear if ventilation is due to temperature or to improve IAQ.

During winter, 16.1% of CO_2 measurements in Santiago corresponded to category I (CO_2 < 800 ppm), 9.6% to category II (800 < CO_2 < 1000 ppm), 22.3% to category III (1000 < CO_2 < 1400 ppm), and 52.1% to category IV (CO_2 > 1400 ppm). In spring, also in Santiago, 79.8% of CO_2 measurements corresponded to category I (CO_2 < 800 ppm), 8.6% to category II (800 < CO_2 < 1000 ppm), 8.1% to category III (1000 < CO_2 < 1400 ppm), and 3.6% to category IV (CO_2 > 1400 ppm).

During winter, 18.6% of CO_2 measurements in Puerto Montt corresponded to category I (CO_2 < 800 ppm), 8.1% to category II (800 < CO_2 < 1000 ppm), 17.4% to category III (1000 < CO_2 < 1400 ppm), and 56.0% to category IV (CO_2 > 1400 ppm). In spring, also in Puerto Montt, 29.6% of CO_2 measurements corresponded to category I (CO_2 < 800 ppm), 9.7% to category II (800 < CO_2 < 1000 ppm), 18.7% to category III (1000 < CO_2 < 1400 ppm), and 41.9% to category IV (CO_2 > 1400 ppm).

Figure 4.4 presents the distribution of CO_2 concentrations in four categories, showing that IAQ tends to be better in spring in Santiago, while time under bad conditions (category 4) diminishes in all cases, compared to winter.

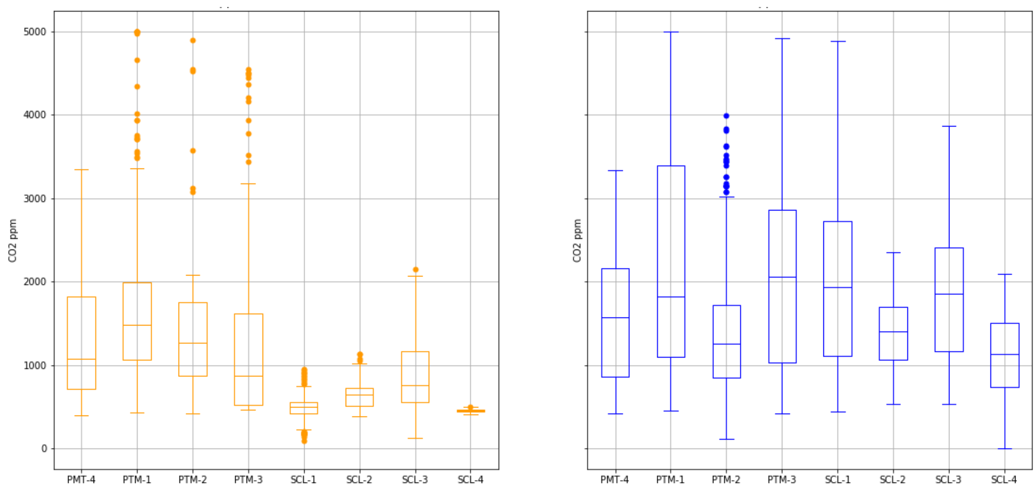


***Figure 4.3:** Distributions of CO_2 ppm concentration in each classroom during occupation time for spring in orange and winter in blue.*

4.3.3 Correlation between CO_2, Occupant Density

Occupant density (OD) can be defined as area per occupant (m^2/p) and has been identified in previous studies (Korsavi et al., 2020a) as correlated with CO_2 concentrations. In the studied classrooms, occupant density was between 1.03 and 2.5 m^2 per student at the time of measure. This OD is much higher than that informed in (Korsavi et al., 2020a), ranging from 1.7 to 2.6 m^2 per person or 1.8 to 2.4 m^2/person in (Clements-Croome et al., 2008). Overall, OD in schools is too high, compared to OD in offices, which is around 10 m^2/person (Clements-Croome et al., 2008). The number of occupants in each classroom was collected, according to the schedule presented in Table 1. The sample size for this analysis was 3270 data points, corresponding to the observations where the number of students in the classroom was recorded.

In Figure 4.5 in area per student is plotted against mean CO_2 levels, showing that mean CO_2 levels will drop if more area is available per person. The variance assigned to the predictor OD is 16.2% ($r2 = 0.162$), which is similar to the values that appear in (Korsavi et al., 2020a) that presented a 17% of CO_2 variation explained by occupant density. The significance of the correlation and the linear model are described in **Table 4-5**. The *p*-value for the whole model is 0.0004212 (significance established at 0.05), confirming that the model is statistically significant.

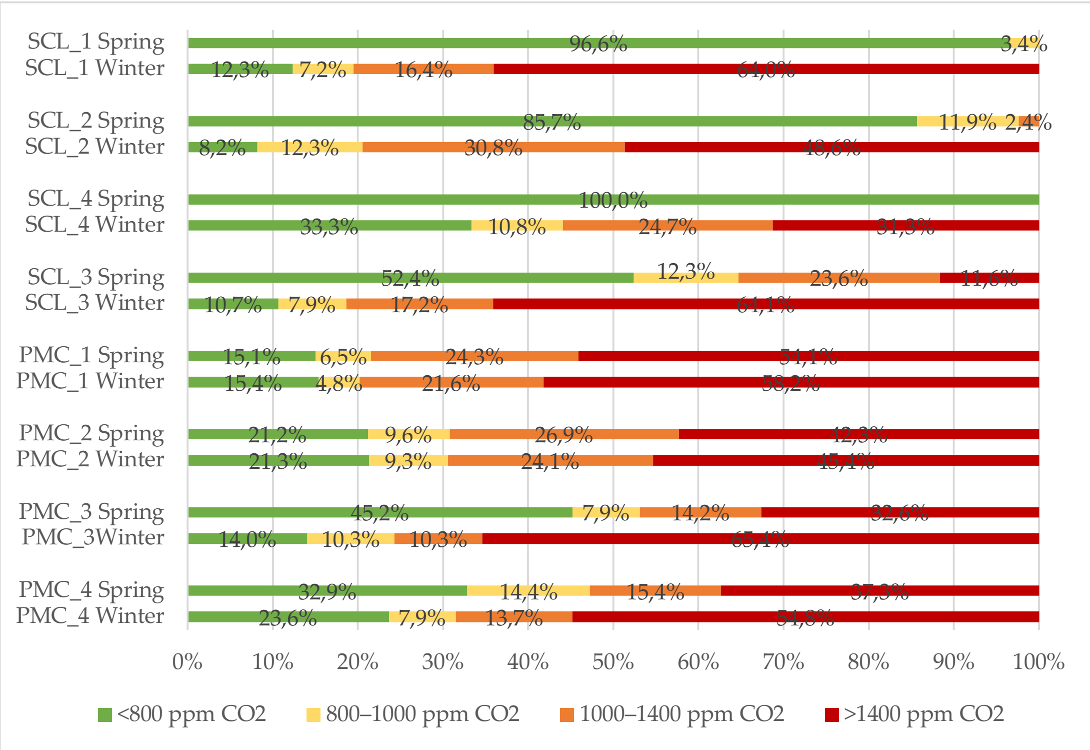


Figure 4.4: *Frequency of CO_2 concentration categorized according to EN 13779:2007*

Table 4-5: *Parameter estimates.*

Variable	*DF*	*Parameter Estimate*	*Standard Error*	*T Value*	*Pr > |t|*
Intercept	1	2681.3	364.	7.348	<0.0001
Area per student	1	−801.	216.7	−3.701	<0.0001

4.3.4 Parameters that Determine Acceptable CO_2 Concentrations

Before conducting Binary Logistic Regression (BLR) analysis, an exploratory linear regression analysis was done. It was found that the factor “city” was a strong differencing factor; therefore, Binary Logistic Regression was calculated for each city separately and then used to rank the parameters regarding their importance for acceptable CO_2 concentrations.

Binary Logistic Regression was applied to explore the relationship between acceptable CO_2 concentrations and several predictor variables. The results of this analysis are maximum likelihood estimates (MLE) and odds ratios (OR). Both describe the likelihood of having acceptable CO_2 concentrations when one of the predictor variables is increased by one unit while the other variables are kept constant.

In Puerto Montt (**Figure 4.6**), the MLE of having acceptable CO_2 concentrations was 3.75 times bigger during spring than in winter. One interpretation of this data is the hesitancy to open windows when the outside air is too cold and would produce discomfort. The following most critical parameter was low inside temperature versus acceptable inside temperature (OR = 2.08, 95%.CI: 4.288), followed by high indoor temperature versus acceptable indoor temperature. These results suggest that the decision to open a window is based on the need to dissipate indoor gains. Therefore, it will be avoided when the indoor temperature is acceptable. It is important to note that outdoor temperatures in this city are still low in spring (average outdoor temperature: 12.7 °C, with a maximum of 20.4 °C) during the occupancy period. The results show a difficulty to maintain both acceptable temperatures and CO_2 levels, simultaneously, which, in this city, means that the heating systems are not designed or used, considering the losses related to ventilation needed for air quality.

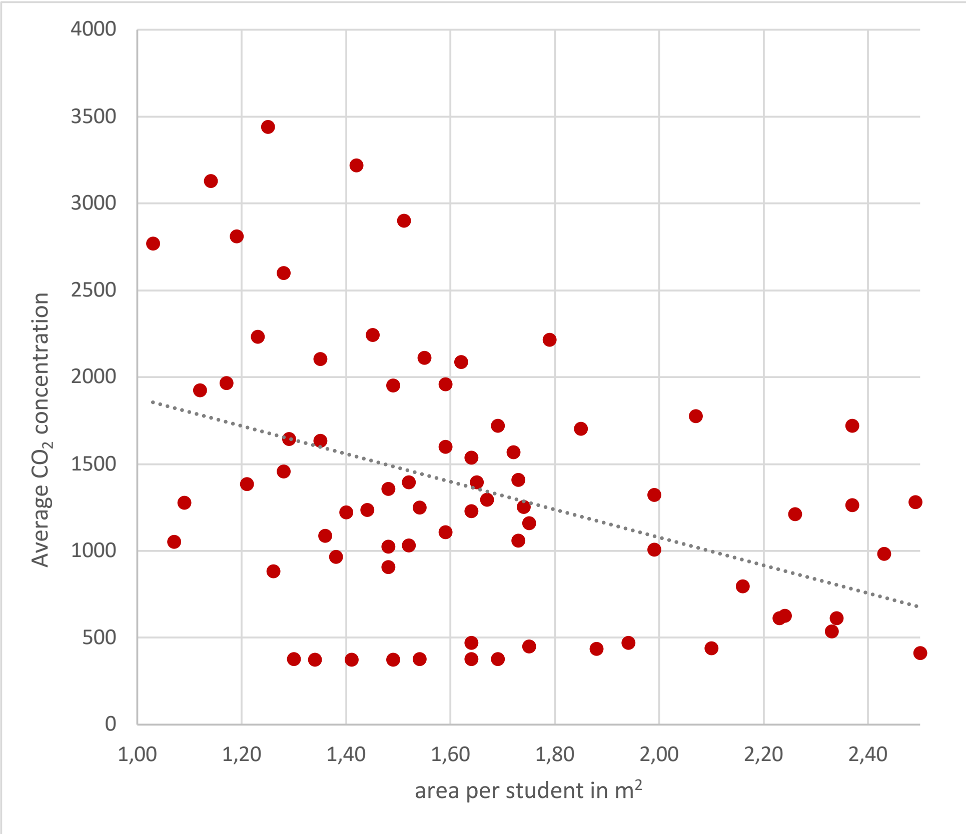


Figure 4.5: *Occupant density in m^2 per student against measured CO_2 levels.*

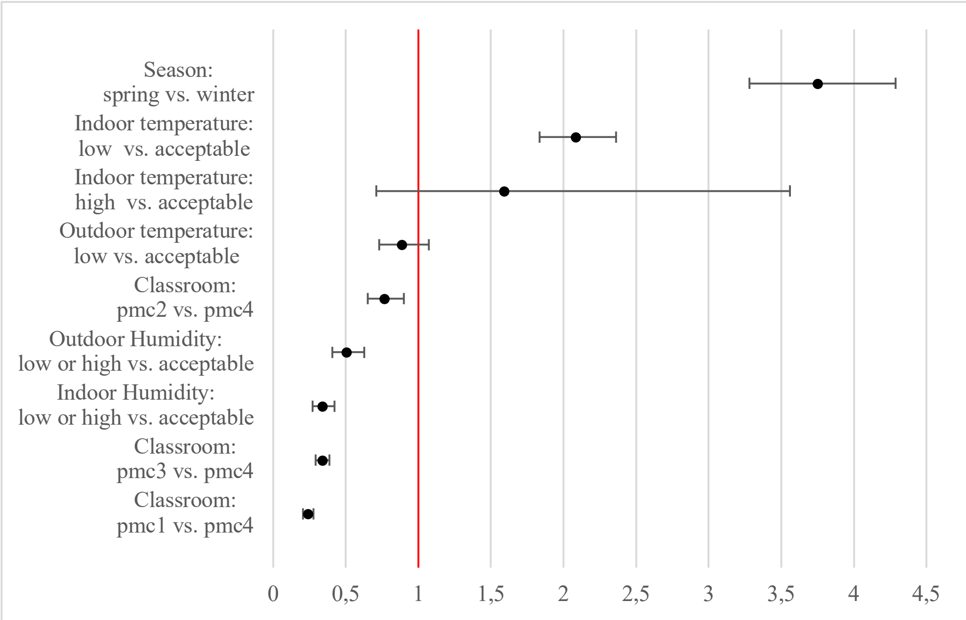


Figure 4.6: *Odds ratios and 95% confidence intervals for acceptable indoor CO_2 concentrations in the heating dominant city Puerto Montt.*

In Santiago (**Figure 4.7**), the MLE of having acceptable CO_2 concentrations was 7.6 times bigger when the indoor air temperature was low than when it was acceptable. It is relevant to note that these classrooms do not have heating devices; therefore, temperatures are low most of the time in winter. The second most relevant factor is seasonality: spring was 2.6 times more likely to have acceptable CO_2 concentrations than winter. The third odd ratio in importance is high indoor temperature, which coincides with the descriptive analysis of the data that showed that the percentage of time with acceptable CO_2 concentrations increased in spring. It is relevant to note that these rooms do not have cooling devices, and that indoor temperatures reached 32.2 °C, demonstrating that, although ventilation strategies managed to lower CO_2 concentration, they could not lower indoor temperatures to the acceptable range.

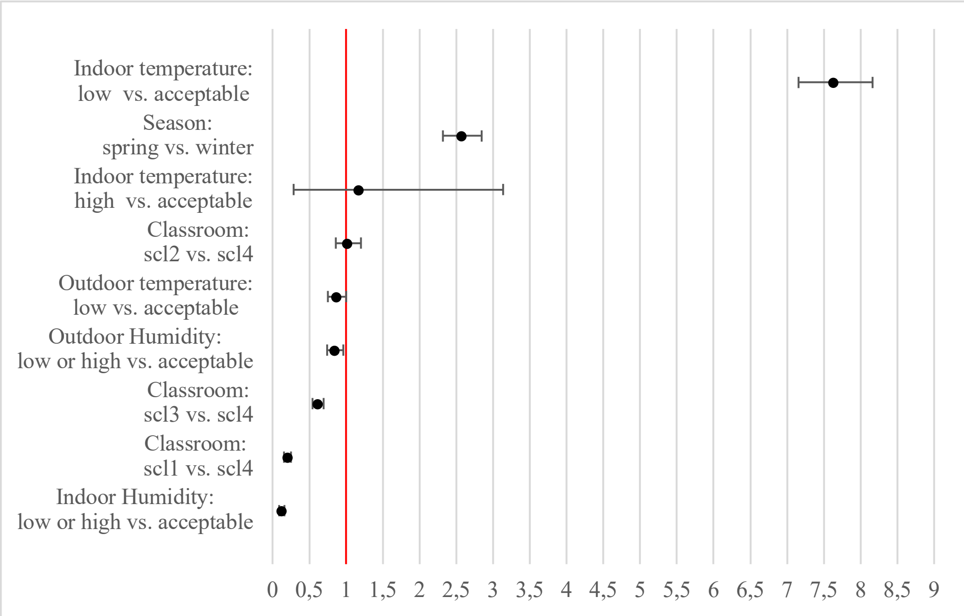


Figure 4.7: *Odds ratios together with 95% confidence intervals for acceptable indoor CO_2 concentrations in the Mediterranean with warm summer city Santiago*

4.3.5 Statistical Test of Individual Predictors

The statistical significance of individual regression coefficients is tested with Wald chi-square, presented in **Table 4-6**. This test confirmed that all variables were significant (p-value < 0.05), except exterior temperature (TempEx), which was not significant in Puerto Montt.

Table 4-6: *Type 3 Analysis of Effects for Puerto Montt and Santiago.*

		PCM		*SCL*			
Effect	DF	Wald Chi-Square	Pr > ChiSq	Effect	DF	Wald Chi-Square	Pr > ChiSq
Temp	2	131.07	<0.0001	Temp	2	1050.95	<0.0001
Temp Ex	1	1.57	0.2099	Temp Ex	1	7.14	0.0075
RH	1	91.80	<0.0001	RH	1	867.76	<0.0001
RH Ex	1	38.35	<0.0001	RH Ex	1	7.82	0.0052
Class	3	450.17	<0.0001	Class	3	1623.94	<0.0001
Season	1	374.96	<0.0001	Season	1	161.85	<0.0001

4.3.6 Validation of Predicted Probabilities

The association of the predicted probabilities and observed responses is evaluated by Kendall's Tau-a, Goodman–Kruskal's Gamma, Somers's D, and c statistic. All of these measures of association were provided by SAS and are presented in **Table 4-7**. The Gamma statistic for Santiago shows that we can predict that the CO_2 concentration will be acceptable, with 47.0% less error, than using chance, and with 50.8% less error in the case of Puerto Montt. If using the more conservative estimation of Somers's D, we can see how much the prediction of acceptable CO_2 levels can be made, based on the independent variable: 45.3% for Puerto Montt and 46.7% for Santiago. The c statistic shows that, for 73% of all possible pairs of CO_2 concentrations, the model assigned them to the correct category.

Table 4-7: *Association of Predicted Probabilities and Observed Responses.*

	PCM	*SCL*	
Somers's D	0.45	Somers's D	0.47
Gamma	0.47	Gamma	0.51
Tau-a	0.19	Tau-a	0.22
c	0.73	c	0.73

4.4 Discussion

4.4.1 Summary of Main Findings

This research presents the analysis of IAQ through CO_2 concentration in schools and seeks to determine the factors that will allow having good IAQ in naturally ventilated schools in Chile. The analysis showed the following: (1) The climatic conditions are a differentiating factor for CO_2 concentrations. In this case, there is a statistically relevant differentiation between CO_2 concentrations in both cities/climates. (2) Acceptable CO_2 concentrations are determined by the seasonality, increasing the chances of desirable CO_2 concentration (bellow 1000 ppm) in spring over winter for SCL and PMC. (3) Indoor temperature is a relevant factor in predicting CO_2 concentrations. High indoor temperatures are related to lower CO_2 concentrations, presumably due to the opening of windows. Low indoor temperature is linked to high CO_2 concentrations, probably because of the need to conserve heat. (4) CO_2 concentrations will be unacceptable during long periods of time in winter to maintain heat in both cities. (5) In SCL, CO_2 concentrations will be acceptable when ventilation is needed to dissipate indoor heat gains. However, this strategy is not suitable for lowering temperatures to acceptable conditions. It is relevant to note that Wargocki and Da Silva showed that providing mechanical cooling in classrooms will restrict window opening (Wargocki & Da Silva, 2015), mimicking the behaviour observed in winter and having a detrimental effect on IAQ. The factors analysed do not explain all the variation in CO_2 concentration. Therefore, it is necessary to consider other factors, like occupant interaction with windows, openable windows area, and window-to-wall ratio.

4.4.2 Design Recommendations

Based on the results of the measurements and the statistical analysis of them, this study recommends the following:

1. Occupant density in classrooms is not as high as designed for (normative allows for 1.1 m^2 per student) but is still high enough to increase concentration after the students arrive at the classroom. Although not demonstrated by the statistical analysis, height, as the third dimension in OD values (m^3/p), has been acknowledged before (Korsavi et al., 2020a) to have an impact on CO_2 concentrations and should be considered, since the requirements allow for low roofs (minimum height of the rooms is 2.2 m (Ministerio de Vivienda y Urbanismo, 2014)).
2. Heating systems need to be designed considering the need for ventilation. The compromise of air quality over thermal comfort is detrimental to students' learning abilities.
3. Window opening could be a good ventilation strategy for IAQ only when thermal comfort requires the same action. If there is a need to conserve heat, other ventilation approaches should be implemented to ensure IAQ.
4. In the case of a Mediterranean climate with warm summer, cooling strategies should be implemented, while noting that mechanical cooling could hinder window opening, as stated in previous research (Gao et al., 2014; Wargocki & Da Silva, 2015).

4.4.3 Strength and Limitation

This study presents the analysis of the effects of climatic conditions, season, and environmental factors on CO_2 concentrations as a proxy for IAQ in Chilean schools. This is the first study of this kind done in a non-industrialized country and the first one considering the impact of different climatic settings.

The methodology used in this research allowed us to identify parameters that affect ventilation through the evaluation of CO_2 concentration in naturally ventilated classrooms. This methodology can be used with other datasets, regardless of location or climatic conditions. The findings can be generalized to classrooms in the same climatic conditions, occupancy, and ventilation system.

One of the limiting aspects of this research is the lack of information on the students' respiratory comfort and children's adaptative behaviours. This information would allow us to better understand the students' engagement with their own comfort and the level of agency they have. In this sense, the use of logbooks to record the opening of windows should be implemented in future research.

4.4.4 Future Work

To further understand the correlation between CO_2 levels and temperature in classrooms in use, other factors that could impact CO_2 concentration should be considered.

Occupant interaction should be further investigated by monitoring patterns of window opening, at least through self-reporting with logbooks.

Our dataset needs to be expanded to increase the representativeness of the sample on the national and international level. The sample should allow for climate-based clustering to represent schools in cooling-dominated climates and mixed climates, such as Iquique and La Serena. Additionally, field measurements and campaigns need to take place to monitor indoor air quality in parallel with acoustics, thermal comfort, and visual parameters, to allow for investigating the influence of air quality on overall indoor environmental quality evaluation.

4.5 Conclusions

All schools in this research suffered from CO_2 concentrations and temperatures outside the thresholds defined during occupied periods. Although this sample is not representative of all school classrooms in Chile, similar results in classrooms designed according to current standards and similar climatic conditions are expected. High occupant density, lack of ventilation design or ventilation systems, and current regulation are systemically related to bad IAQ.

This research aimed to identify the relation between air quality and building-related and occupant-related factors in free-running and naturally ventilated primary schools during typical use. The methodology proposed proved suitable and provided the expected results. This research confirmed the variability of CO_2 concentrations, depending on season and indoor temperature, where IAQ was relegated to second-place relevance by the need to ensure comfortable temperatures. The statistical significance of individual regression coefficients confirmed that all variables were significant (p-value < 0.05) except exterior temperature (TempEx), which was not significant in Puerto Montt. The independent variables in this study were not able to predict all the variation in CO_2 concentration, meaning that there could be others that should be included in further research

5 Methodology for the definition of weighted environmental comfort index for primary schools

This chapter presents a methodological approach to the development of an index that summarizes the evaluation of Indoor Environmental Quality (IEQ) from the perspective of students in school classrooms.

In this sense, this first methodological approach will position the decisions to take when designing a survey and measurement protocol that allows to build an index.

This chapter was developed with the existing dataset provided by CITEC UBB during the COVID-19 pandemic. To advance in the development of the index while schools were closed. This dataset was used to explore different approaches found in the literature to build an index, The exploration with this dataset helped to define the information to be gathered via survey and measurements, as well as evaluating the suitability of one of the existing surveys in Spanish.

The results of this chapter showed the need for the development of a survey asking about IEQ general perception, as well as preference, acceptability, and sensation of each parameter. It also highlighted the relevance of equipment selection, pretesting and validation of measured data.

The conceptual study framework of this chapter is shown in Figure 5.1. This graphic represents the main steps of the research workflow.

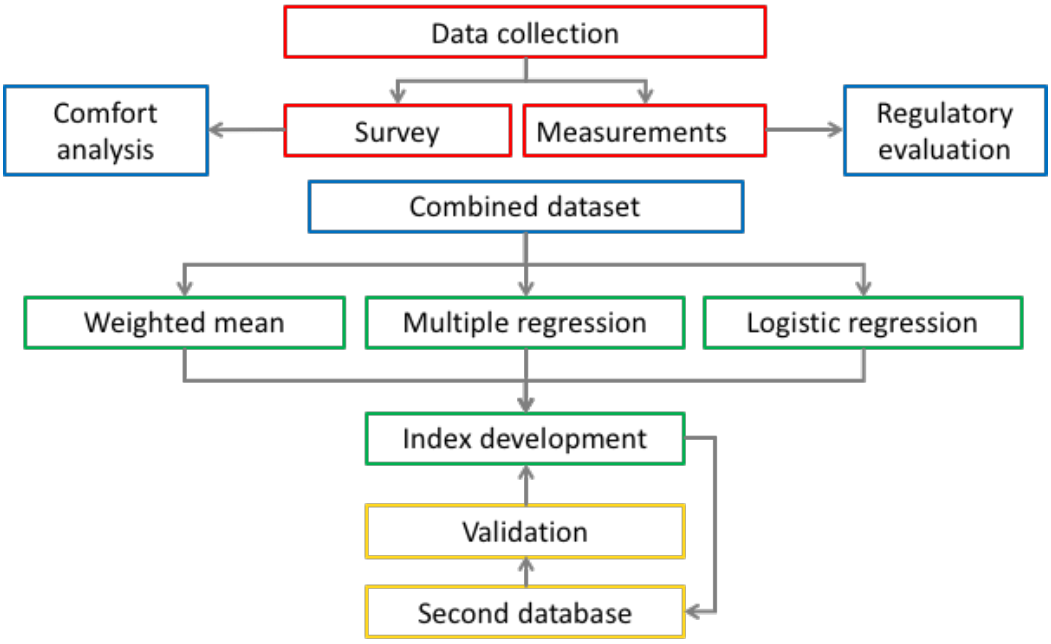


Figure 5.1: *conceptual study framework for the development of an index*

5.1 Methodology

The three main objectives of this research are to correlate subjective evaluation of the four main aspects of IEQ with the physical measurements; then compare IEQ evaluation with current standards to evaluate if occupants are forgiving of the indoor environment and finally; propose a methodology for the definition of a weighted environmental index for IEQ in naturally ventilated classrooms, based on the study of environmental comfort and the corresponding environmental variables.

To explore the definition of a weighted environmental comfort index, three statistical analyses will be applied to the dataset; Principal Component Analysis; Multiple Linear Regression and Binary Logistic Regression.

The dataset used for this research corresponds to a POE conducted in twelve school classrooms in the southern city of Coyhaique, Chile. The survey and measurements were conducted by CITEC UBB to determine energy demand and propose improvements to the building envelope to lower the energy demand of the buildings. The six schools were selected to represent the different typologies of schools existing in the region. From each school, two classrooms and two management areas were surveyed. In this research, only the data for the classrooms will be used.

The dataset was secondary data provided by CITEC UBB with the approval of the Ministry of Education. This dataset consisted of survey responses, indoor and outdoor environmental measurements, planimetric information, photos, and some constructive details. The field study was conducted in 2019 during the winter month of October.

Table 5.1 presents a summary of the characteristics of the case studies. The classrooms had between 1,59 and 2,76 m² per student. All classrooms had windows that allowed the penetration of natural light, as well as proper and functional artificial lighting. The window area was between 3,0 and 13,9 m² with the orientation described in **Table 5.1**. All classrooms had fluorescent tubes for artificial lighting. The different finishings for walls, floors and ceilings are described in the table. **Figure 5.2** presents some pictures of the surveyed classrooms.

5.1.1 Case study

Coyhaique is a regional capital and has services and governmental offices and a population of 50,000 inhabitants. The city is located to the east of the Andes Mountains, in Chilean Patagonia at an average altitude of 310 meters above sea level, where the Simpson and Coyhaique rivers converge. Summers are humid and with maximum temperatures of up to 28°C, while in winter the temperature drops drastically. With a minimum of -15°C, Precipitation is between 800 and 1200 mm per year, with abundant winter snow. The absolute minimum winter temperature reaches -26,4°C and the absolute maximum in summer is 35,7°C.

According to the Köppen classification (Sarricolea et al., 2017) the climate in this city is a Mediterranean climate with a mild summer (Csc). The city has 2694 HDD with a base temperature of 15,5°C and 14 CDD with a base temperature of 24°C (BizEE Software, 2021), Other factors that characterize this city is the pollution during winter (Perez et al., 2020), The pollution is mainly related with the geography of the city, that is in a closed valley, the low ventilation during winter and the heating of houses and some public buildings with wood-burning stoves. Two factors that increase the pollution are the quality of the wood and the low efficiency of the stoves (Boso et al., 2020), while the low ventilation of the city explains the permanence of the smog over the city.

Figure 5.2: *Classrooms surveyed*

Table 5.1: *Characteristics of the twelve classrooms studied in Coyhaique, Chile.*

CLASSROOM	1	2	3	4	5	6	7	8	9	10	11	12
CODE	Coy011	Coy012	Coy021	Coy022	Coy031	Coy032	Coy041	Coy042	Coy051	Coy052	Coy061	Coy062
WITH (M)	7,2	7	6,2	6,4	7,1	7,3	8,9	8,9	8,6	8,7	8,8	8,9
LENGTH (M)	5,5	5,9	7,8	6,3	7	7	5,7	5,7	6,1	6	6,3	5,9
AREA (M2)	53,8	41,3	48,36	40,32	49,7	51,1	50,73	50,73	52,46	52,2	55,44	52,51
LEVEL	1	1	1	2	3	3	1	1	1	2	2	1
VOLUME (M3)	134,5	99,1	106,4	112,9	137,7	141,5	142,0	142,0	146,9	146,2	155,2	136,5
NO SEATS	28	26	24	20	18	28	28	28	29	30	30	24
AREA/STUDENT	1,92	1,59	2,02	2,02	2,76	1,83	1,81	1,81	1,81	1,74	1,85	2,19
N° WINDOWS	3	6	3	1	2	2	3	3	3	4 + 1	4	3
WINDOW AREA	3,0	7,1	8,6	9,9	10,8	10,8	13,9	13,9	8,1	8,1	9,0	15,7
WINDOW ORIENTATION*	E	S / W	W	N	W	NE	SW	SE	NW	NW	SW	N
LIGHT SOURCE	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial	natural and artificial
TYPE OF LIGHTING	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube	fluorescent tube
WALL MATERIAL	paint	wood	paint	paint	paint	paint	paint	paint	paint	paint	paint	paint
CEILING MATERIAL	paint	paint	paint	paint	paint	paint	painted wood	paint	painted wood	painted wood	paint	paint
FLOOR MATERIAL	ceramic	ceramic	vinyl	vinyl	vinyl	vinyl	vinyl	vinyl	wood	wood	vinyl	vinyl

*** THE SCHOOLS ARE IN THE SOUTHERN HEMISPHERE; THEREFORE, THE NOON SUN COMES FROM THE NORTH,**

Occupants

As summarized in **Table 5.2**, all the respondents were school students between 10 and 17 years old. Gender is distributed between 46% of females and 52% of males, while only 3% of the respondents did not answer this question.

Table 5.2: *Characteristics of the children that participated in the POE in Coyhaique, Chile.*

GENDER	CLASSROOM								
	coy012	coy021	coy031	coy032	coy041	coy051	coy052	coy061	coy062
F	138 (55%)	93 (39%)	124 (90%)	148 (65%)	71 (32%)	103 (31%)	110 (40%)	58 (27%)	154 (52%)
M	112 (45%)	131 (55%)	0	77 (34%)	148 (68%)	217 (65%)	150 (55%)	158 (73%)	140 (48%)
N/A	0	14 (6%)	14 (10%)	3 (1%)	0	15 (4%)	13 (5%)	0	0
AGE GROUP	16-17	13-14	16-17	15-16	11-12	12-13	13-14	15-16	9-10

5.1.2 Data collection

Survey

The subjective perception of the IEQ from the students in class was collected via a POE paper-based survey, The survey was based on the thermal comfort survey developed by Trebilcock et al. (2017b) and adapted to include the other IEQ parameters The full list of questions is presented in ***Annex*** *1*. The survey application uses transversal sampling and "point-in-time" questions. These types of questions are suitable for children as they don't rely on memory or require them to reflect on previous experiences. The survey was applied three times a day to evaluate the changes in their comfort that occurred during teaching hours.

The survey is divided into six main domains. The first domain collects the demographic characteristics of the respondents as gender, location in the classroom, date, and classroom. The second domain gathers information about the personal factor that are known to affect thermal comfort such as clothing and activity prior to entering the classroom. The third domain collects information about thermal comfort, the fourth about acoustic comfort, the fifth about IAQ and the sixth and last about visual comfort. The question dealing with perception and preference are evaluated on a Likert-scale, while questions dealing with sources of discomfort vary in the number of possible answers.

Questionnaires were filed by 315 students in 6 schools and 12 different classrooms for 5 days. Finally, 4725 completed questionnaires were received.

Monitoring of Environmental Variables

Monitoring of environmental variables was done for a period of five consecutive days representing a typical winter school week. Air temperature, humidity and CO_2 concentrations were measured at 30-minute intervals. The measuring device was located on a pole in the centre of the classroom, protected from direct solar radiation, and manipulation. The device was located at 1,1m as recommended by ISO 7726 (ISO 7726 Ergonomics of the Thermal Environment — Instruments for Measuring Physical Quantities, 1998), The device was installed on the weekend before measurement and collected data continuously for the 5 days, although only data for occupied period will be used in this study.

Acoustic variables were measured when the room was unoccupied. Façade sound isolation was measured according to ISO 16283-3:2016 (Acoustics - Field Measurement of Sound Insulation in Buildings and of Building Elements - Part 3: Façade Sound Insulation (ISO 16283-3:2016), 2016). Reverberation time according to ISO 3382:2008 (Acoustics - Measurement of Room Acoustic Parameters - Part 2: Reverberation Time in Ordinary Rooms (ISO 3382-2:2008), 2008). And Sound isolation of floors (when in contact with other rooms) according to ISO 16283-2:2020 (Acoustics - Field Measurement of Sound Insulation in Buildings and of Building Elements - Part 2: Impact Sound Insulation (ISO 16283-2:2020), 2020).

Illumination levels were measured, but due to a calibration error, were not consistent. Based on the CIE standard skies for the city of Coyhaique calculated for October (M. B. Piderit et al., 2014) it is assumed that the sky is overcast therefore artificial light is used in all classrooms during lectures. Other architectural indicators like window area and location were also measured.

5.1.3 Statistical analysis

The main objective of this research is to propose a methodology for the definition of a weighted environmental comfort index for primary schools, based on the study of environmental comfort and the corresponding environmental variables. In this sense, the statistical analysis of the data will allow us to pair measured variables with the comfort perception of the students, while also describing this correlation.

Dataset

The data used in this research was gathered through a post-occupancy evaluation (POE) to evaluate energy use and evaluate strategies to improve IEQ while diminishing energy use. Considering the climatic conditions of the city, data was gathered only for winter. In shoulder season heating is still needed, while artificial lighting should be less needed. There is no data to support this claim, other than the subjective evaluation of the local representative of the Ministry of Education.

Descriptive statistics

The first approach to data analysis was done through descriptive analysis, First, indoor temperature and relative humidity were matched with outdoor data over a school day, and average, minimum and maximum temperatures and CO_2 concentrations were estimated during occupied hours for each school. Afterwards, distributions, outliers, and variations both within and between schools for each variable were analysed.

Indoor temperatures ranged from 13,1ºC to 23,9ºC during the measurement period, while indoor relative humidity ranged from 35% to 62%. CO2 concentration had a minimum of 415 ppm and a minimum of 2965 ppm during occupied times. Acoustic indicators were measured when the classrooms were unoccupied and they reflect the insulation of the materials, independent of the use. The Airborne sound insulation of the façades ranged between 20 and 30 dB(A). Airborne sound insulation between spaces ranged between 24 and 46 dB(A). And Impact Sound Insulation between 62 and 75 dB

Table 5.3: *Descriptive statistics of indoor environmental variables per classroom in Coyhaique, Chile*

	Indoor Globe Temperature (°C)			*Indoor Relative Humidity (%)*			*Indoor CO_2 concentration (ppm)*			*$D_{ls,2m,nT}$ (dB(A))*	*TL*	L'_n
	med,	min,	max,	med,	min,	max,	med,	min,	max,			
coy011	21,9	19,6	22,5	45	43	49	1452	1259	1958	30	43	75
coy012	19,1	18,5	20,1	59	56	62	1731	1388	2965	20	32	75
coy021	15,2	13,1	16,0	66	59	68	197	1314	2363	29	46	65
coy022	19,0	14,9	20,1	50	46	55	2126	518	2504	29	44	65
coy031	16,6	15,8	18,8	49	48	53	1146	814	1421	22	34	75
coy032	18,1	14,7	18,1	48	43	52	1168	833	1291	22	34	75
coy041	20,3	18,6	21,5	44	41	50	1802	528	2743	28	39	-
coy042	17,9	17,5	19,7	41	39	44	566	415	848	24	24	-
coy051	20,3	17,6	21,8	49	46	52	1334	1025	2051	22	36	62
coy052	21,8	20,4	23,9	38	35	39	1132	892	1382	20	33	62
coy061	16,9	14,2	19,3	48	43	52	730	622	859	25	43	74
coy062	18,6	17,2	19,4	44	41	46	904	757	957	20	28	74

5.1.4 Index development

The index will be developed in two stages, In the first, the weighting scheme for the four aspects of IEQ will be defined based on Principal Component Analysis**.** In the second stage, each comfort vote will be defined based on the measured parameters, resulting in a two-level equation.

Weighting scheme for the four aspects of IEQ

Since the survey didn't ask about the general comfort perception of the occupants, a different approach was developed to weigh the relevance of each aspect of IEQ.

To define the weight that the evaluation of each aspect of IEQ has on the overall comfort perception, Principal Component Analysis (PCA) methodology was used.

Regression analysis

To assess comfort using a combined index reflecting both measurements of environmental variables and sensation votes, a regression analysis was conducted. Firstly, to select the variables to be used in the development of the index, Spearman correlation was tested between each variable and its corresponding survey question. Spearman's correlation is used for non-parametric data and reflects the strengths of the relationship between paired data(A, Field & Iles, 2016; A, P, Field, 2012). This test is suitable for continuous and ordinal data as is this dataset. For all statistical analyses, R Software and RStudio were used.

The second part of the statistical analysis aims to define an index that summarizes thermal, respiratory, visual, and acoustic comfort, and that could predict the perception of students based on measured data. Therefore, environmental variables are used as predictors of comfort.

Based on the literature review and according to the characteristics of the dataset the following statistical analyses were performed:

Multiple Linear Regression: This model describes how a dependent variable, in this case, comfort, depends linearly on several predictor variables. As discussed in a previous publication (Diaz, Cools, et al., 2021) linear models are not recommended for data where observations are dependent. For this research, we decided to use this method to compare the resulting index.

Binary Logistic Regression: This model describes the probability of a binary dependent variable result, based on several predictor variables. In this case, the result analysed is having a comfort vote.

5.2 Results

In this section general descriptive statistics of the dataset are presented. Afterwards, linear regressions are presented by variable. If necessary, the process to define thresholds is also presented as a result. Afterwards, the Binary Logistic Regression and the model that arises are presented.

5.2.1 Perception of the indoor environmental quality

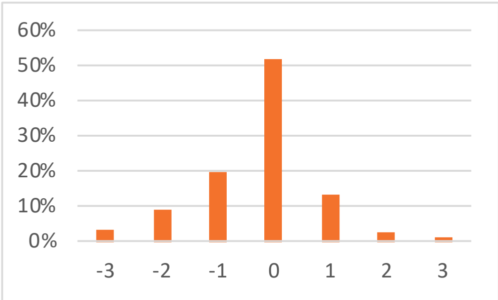
The frequency of responses of perception of the IEQ is presented in **Figure 5.3**. Temperature was mostly considered as comfortable (51,4%), the data is skewed to the colder side which is consistent with the survey being conducted in winter with outside average temperatures below 0°C.

The perception of the noise inside the classrooms is skewed to not noisy, extremely noisy is mentioned in only 0,7% of the responses.

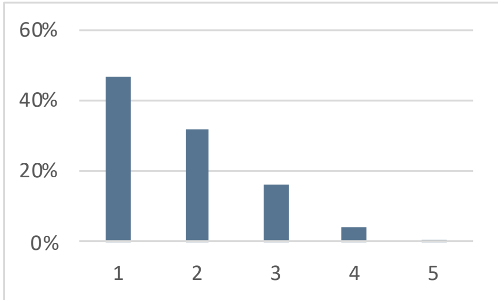
Light is perceived mostly as adequate (69,6%), the second percentage is low (13,5%) followed by high (10,3%). This is consistent with the design of the classrooms that have a minimum of 16% of openings in the main façade according to local regulations (Ministerio de Vivienda y Urbanismo, 2006).

The overall frequency of Air Sensation votes (ASV) shows that a high proportion of votes corresponds to “agree” (37,87%), followed by “It does not matter to me” (29,33%), “strongly agree” (12,11%) and “strongly disagree” (5,49%).

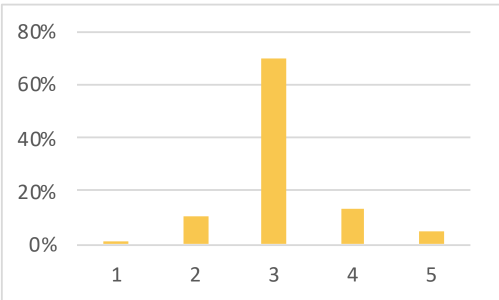
To evaluate IEQ, the perception responses were classified as comfortable (votes between -1 and 1), For thermal; between “cool” and “warm “, for acoustic between “not at all noisy” and “moderately noisy”. Air quality was defined as comfortable between “strongly agree “and “undecided”. Visual comfort was defined between “high“ and “low“.



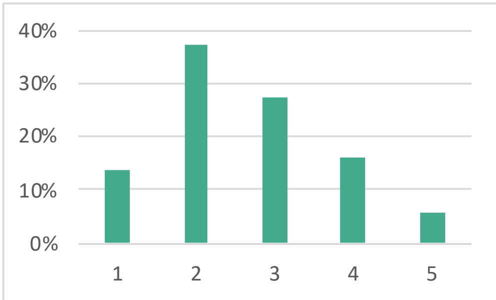
Right now, how do you feel the temperature?
(-3) too cold, (-2) cold, (-1) cool, (0) comfortable, (1) warm, (2) hot, (3) too hot



Right now, how loud is the ambient noise?
(1) not noisy, (2) slightly noisy, (3) noisy, (4) very noisy, (5) extremely noisy,



Right now, the lighting on your desk is:
(1) excessive, (2) high, (3) adequate, (4) low, (5) too low



Right now, do you find that ventilation or air quality is adequate?
(1) strongly agree, (2) agree, (3) undecided, (4) disagree, (5) strongly disagree,

Figure 5.3: *Normal distribution of survey responses in Coyhaique, Chile*

The aspect of comfort that is perceived as comfortable for most respondents is acoustic comfort (94,94%) followed by visual (93,48%), thermal (84,10%) and air quality (78,40%). If four aspects are considered, comfort in all of them is the prevalent answer (63,01%). Other possible combinations and their corresponding occurrence are summarized in Figure 5.4.

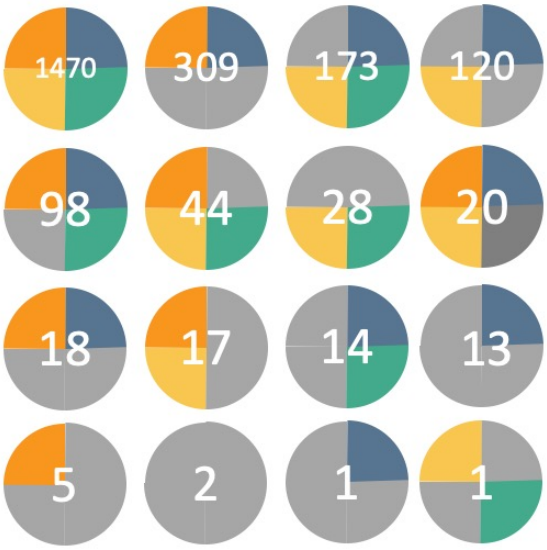


Figure 5.4*: Grouping of acceptability evaluation according to children's perception of the four aspects of IEQ*

5.2.2 Weighting scheme for the four aspects of IEQ

Since the survey didn't ask about the general comfort perception of the occupants, a different approach was developed to weigh the relevance of each aspect of IEQ.

To define the weight that the evaluation of each aspect of IEQ has on the overall comfort perception, Principal Component Analysis (PCA) methodology was used. To decide on the relevance of the Principal Component Analysis (PCA), Bartlett's test of sphericity was carried out, demonstrating the hypothesis that the correlation matrix differs from the identity matrix. Therefore, it is appropriate to carry out the analysis. Similarly, the Kaiser-Meyer-Olkin index (KMO= 0,65) was calculated, supporting the use of the technique.

Once the standardised variables were obtained, a principal component analysis was carried out for each of the domains, reduced to a single factor that allowed the representation of each of them to be obtained, namely: TSV (Thermal sensation vote), NSV(Acoustic sensation vote), IAQ (Indoor Air Quality) and VSV(Visual sensation vote), associated to the survey questions in **Table 5.4**.

Then, a principal component analysis was performed again with the four components obtained, where the first principal component thus obtained represents the comfort index (Ind_Conf) for each of the individuals in the sample.

Once the index (Ind_Conf) was found, and to facilitate its understanding and interpretation, it was typified in such a way that its values were between 0 and 100, For this, the index was subtracted from its minimum value, then this result was divided by its maximum and multiplied by 100:

$$Ind_{\mathrm{IEQ}} = 0{,}55 \times NSV + 0{,}48 \times IAQ - 0{,}47 \times TSV - 0{,}02 \times VSV \qquad \text{Eq.5.1}$$

Acoustic sensation vote (NSV) has the highest weight, followed by Indoor Air Quality (IAQ), both with a positive impact, Thermal sensation vote (TSV) and Visual sensation vote (VSV) dimensions have a negative impact, while the weight of VSV is neglectable.

Table 5.4: *Questions used to build the index*

	How do you feel the temperature at this moment						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Q1 (TSV)	very cold	cold	a little cold	comfortabl e	a little too hot	hot	very hot
	At this time, how loud is the ambient noise?						
	1	**2**	**3**	**4**	**5**	-	-
Q7 (NSV)	Not at all noisy	Slightly noisy	Moderatel y noisy	Very noisy	Extremel y loud	-	-
Q13 (IAQ)	**At this time, do you find that ventilation or air quality is adequate?**						
	1	**2**	**3**	**4**	**5**		
	Strongly agree	Agree	It does not matter to me	Disagree	Strongly disagree	-	-
Q15 (VSV)	**Right now, the lighting on your desk is:**						
	1	**2**	**3**	**4**	**5**		
	Excessiv e	high	Adequate	Low	Very low	-	-

The descriptive statistics of the index are presented in **Table 5.5**, which indicates that the calculated index (through PCA) has a mean of 0 and a standard deviation of 1, equivalent to the parameters of a standard normal distribution. It should be noted that although the index does not comply with the assumption of normality, the parameters of a standard normal are favourable.

Table 5.5: *descriptive statistics of the index*

RANGO	MIN	MAX	MED	SD	ASIMETRY		KURTOSIS	
					Statistic	Typical error	Statistic	Typical error
4,772	-1,974	2,798	,000	1,000	,477	,055	,045	,109

5.2.3 Thermal comfort

Thermal comfort was studied by measuring indoor temperature and relative humidity and through questions on sensation, preference, acceptability, clothing insulation and previous activity level. Outdoor data was gathered from a neighbouring climatic station[11].

Multiple Linear Regression: Thermal comfort

The first part of the study uses the Spearman correlation test to select the significant variables to predict TSV (**Table 5.6**). This was made through hierarchical regression. To assess the fit of the model the multiple R^2 represents the correlation between the predicted and observed values of the outcome when a value of 1 represents a perfect fit. It is relevant to note that having more predictors will artificially increase the value of R^2.

[11] Teniente Vidal station, code 450004, 2019 from climatologia.meteochile.gob.cl/

Table 5.6: *Hierarchical regression of thermal comfort*

	R^2	*B*	*Std, dev,*	*t-value*	*Pr(>|t|)*
Step 1	0,19				
Constant		-3,00	0,12	-24,58	<0,001
Top		0,15	0,01	22,28	<0,001
Step 2	0,19				
Constant		-2,64	0,24	-11,14	<0,001
Top		0,14	0,0073	18,98	<0,001
CO_2		-0,00002	0,00002	-0,93	0,35
HR		-0,004	0,003	-1,39	0,164
Step 3	0,2				
Constant		-2,57	0,27	-9,45	<0,001
Top		0,14	0,0093	15,72	<0,001
CO_2		-0,00004	0,00003	-1,34	0,181
HR		-0,001	0,013	-0,48	0,635
T ext		-0,001	0,001	-0,98	0,326
HR ext,		0,003	0,002	-1,34	0,179

The t-test associated with the variables CO_2, Indoor relative humidity (HR), Outdoor temperature (Text) and outdoor relative humidity (HRext) shows that they are not significant. While Operative temperature (T_{op}) remains significant in all three models. To compare the three models the ANOVA was calculated. It showed no improvement in the fit of the model by using more variables. Therefore, the first model (step one), where only T_{op} is used as a predictor has a better fit to describe thermal comfort. The linear regression model is presented in Eq.5.2.

$$TSV = 0{,}15x\,T - 2{,}25 \qquad \text{Eq.5.2}$$

Adaptative Thermal comfort

To develop an equation able to predict the exact vote of the child-occupant of a classroom, a thermal comfort equation was developed based on the adaptive comfort model.

The prevailing mean outdoor temperature (θrm) for the period under study, which considers a 7-day period before the day under study, was found below 10°C. Ranging between 2,70°C and 5,66°C. This meant that thermal acceptability according to EN16798 (formerly15251) (EN 16798-3 : Energy Performance of Buildings - Ventilation for Buildings - Part 3: For Non-Residential Buildings - Performance Requirements for Ventilation and Room-Conditioning Systems, n.d.) could not be calculated based on outdoor temperatures, as the lower comfort limit is 15°C. The same was true for

ASHRAE 55–2017 which sets the limit at 10°C. The annual **θ**rm for the city of Coyhaique is below 10°C 59% of the time and below 15°C 96%, For the three months of winter, there is no **θ**rm over 10°C, while **θ**rm over 15°C are only in January and February that correspond to the summer months.

Thermal perception (TSV) according to the survey results was mainly neutral, between -1 to 1 (82,77%). With cold (9,62%) and very cold (4,15%) in second and third place. Hot represented only 2,52%, while very hot was only 0,94% of the 2026 votes.

Based on neutral TSV and indoor temperatures, the comfort temperatures (M. A. Humphreys et al., 2007) for the students range from 9,36°C to 26,75 °C.

Adaptive comfort model

Coinciding with the study from, (Corgnati et al., 2009) and (Teli et al., 2013), the thermal sensation vote (TSV) and thermal preference vote (TPV) were checked for consistency by computing the following formula:

$$TSV + TPV \leq 3 or > 3$$

Eq. 5.3

This eliminated cases where, for example, the thermal sensation vote would be “very cold” and the preference vote would be “I wish the room was much colder”. Through this process, 664 answers were deleted, With the consistent surveys, a new database was created that combined survey results with indoor and outdoor measurements. Using this database, the comfort temperatures for each survey were calculated using Griffiths equation (M. A. Humphreys et al., 2007):

$$T_{Conf} = T_{op} - \frac{TSV}{b}$$

Eq. 5.4

Based on (Perez-Fargallo et al., 2018) the value of b = 0,5 will be used in this analysis and will be compared against the results of this study.

To define the neutral temperature based on the prevailing outdoor temperature, a linear statistical regression was performed to find a correlation between both values. Correlation is a statistical measure that suggests the level of linear dependence between two variables. In this case, the correlation between Comfort temperature and Prevailing mean outdoor temperature is 0,075. The linear model for comfort temperature is, where the estimates are presented in **Table 5.7**.

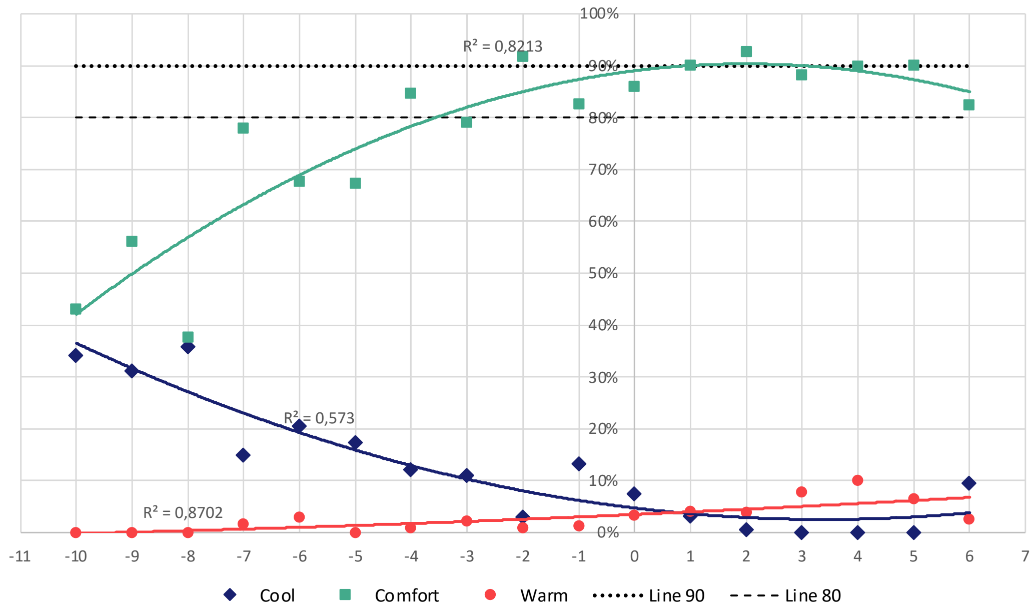
$$TN = 0{,}24 * \theta RM + 17{,}91 \qquad \text{Eq.5.5}$$

***Table 5.7**: Adaptative comfort equation's estimates*

SE	t-value	P-value
0,299	59,74	< 2e-16

The TSV that accounts for 90% of comfort votes (Between -1 and 1) is related to temperatures between 3 °C above and -2 °C below the neutral temperature calculated in Eq.5.5. For 80% of comfortable votes, the range is between 6 and -4°C from the neutral temperature, as shown in **Figure 5.5**. These threshold temperatures are low for both minimum and maximum comfort temperatures when compared to EN 16798-1. The range of temperatures of 5°K (90% of comfort votes) is consistent with category II which has 6°K between the lower and the higher comfort temperature. While the range of 10°K (80% of comfort votes) is consistent with category IV which has 10°K between the lower and the higher comfort temperature, between 18°C and 28°C.

***Figure 5.5:** Proportion of thermal sensation votes from offset from neutral temperature using the*



proposed model

5.2.4 Air Quality Perception

Air quality was monitored for a period of five consecutive days at 30-minute intervals representing a typical school week, The distribution of CO_2 concentrations in each classroom is shown in **Figure 5.6** for occupied times, The median for the whole dataset is 1217 ppm, although variability between classrooms is high. IAQ was questioned by asking about the adequacy of ventilation and reasons for inadequacy if found.

The CO_2 concentration data were categorized based on EN 16798-1 with a base of 400 ppm. Each category is described in Table 5.8, where they are related to the mean temperature and its SD.

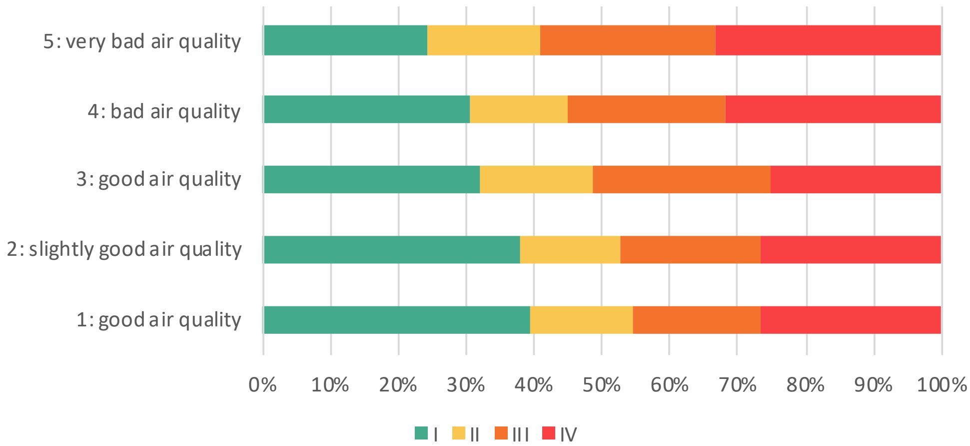


Figure 5.6: *Frequency of CO_2 concentration categorized according to EN 16798-1 related to ASV*

Table 5.8: *CO_2 categories, distribution, and associated temperature*

CATEGORIES	CO_2 LEVELS	FREQUENCY	TEMP MEAN	SD OF TEMP
CATEGORY I	<950	38,64%	17,63 °C	3,20 °K
CATEGORY II	950< CO_2> 1200	16,67%	18,54 °C	2,78 °K
CATEGORY III	1200< CO_2> 1750	18,18%	18,96 °C	3,29 °K
CATEGORY IV	1750< CO_2	26,52%	18,13 °C	3,47 °K

Multiple Linear Regression: Air Quality sensation

The hierarchical regression performed shows that CO_2 is a significant predictor only in the initial model (**Table 5.9**). Then, T_{op} and HR become significant. By comparing the R^2 of the three models, it is clear that model two is better at predicting the outcome. To confirm this the ANOVA was calculated. It indicated an improvement in the fit of the model by using the second step. Therefore, the second model (step two), where T and HR are used as a predictor has a better fit.

Table 5.9: *hierarchical regression of Air Quality sensation*

	R^2	B	Std, dev,	t-value	Pr(>|t|)
Step 1			0,006		
Constant		0,84	0,017	48,45	<0,0001
CO_2		-0,00003	0,000009	-3,468	<0,0001
Step 2			0,027		
Constant		0,82	0,10	7,901	<0,0001
CO_2		-0,00001	-0,00001	-1,073	0,283
T		0,01	0,003	3,184	<0,001
HR		-0,004	0,001	-2,783	<0,001
Step 3			0,027		
Constant		0,84	0,118	7,104	<0,0001
CO_2		-0,000006	0,00001	-0,461	0,644
T		0,008	0,004	1,926	0,054
HR		-0,005	0,002	-2,788	<0,001
T ext		0,004	0,005	0,902	0,367
HR ext		0,0007	0,0009	0,686	0,493

Binary logistic regression

Variables that were correlated with comfort vote on the linear regression were considered to develop a binary logistic regression, The estimates are presented in The results of this analysis are maximum likelihood estimates (MLE) and odds ratios (OR). Both describe the likelihood of having acceptable air quality when one of the predictor variables is increased by one unit while the other variables are kept constant.

Table 5.10 *and odds ratios are presented in* ***Figure 5.7****, the regression model is presented in Eq.5.6.*

$$IAQ = 0{,}058\ Top + 0{,}03HR + 1{,}84 \quad \text{Eq.5.6}$$

The results of this analysis are maximum likelihood estimates (MLE) and odds ratios (OR). Both describe the likelihood of having acceptable air quality when one of the predictor variables is increased by one unit while the other variables are kept constant.

Table 5.10: *Binary regression estimates for IAQ: indoor air quality,*

VARIABLE	ESTIMATE	S E	p-value
(INTERCEPT)	1,84	0,579	0,0015
TEMP	0,06	0,019	0,0023
HR	-0,03	0,007	<0,001
GOODNESS-OF-FIT: **AIC: 1712,6 DEVIENCE: 1706,6, NULL DEVIANCE: 1752**			

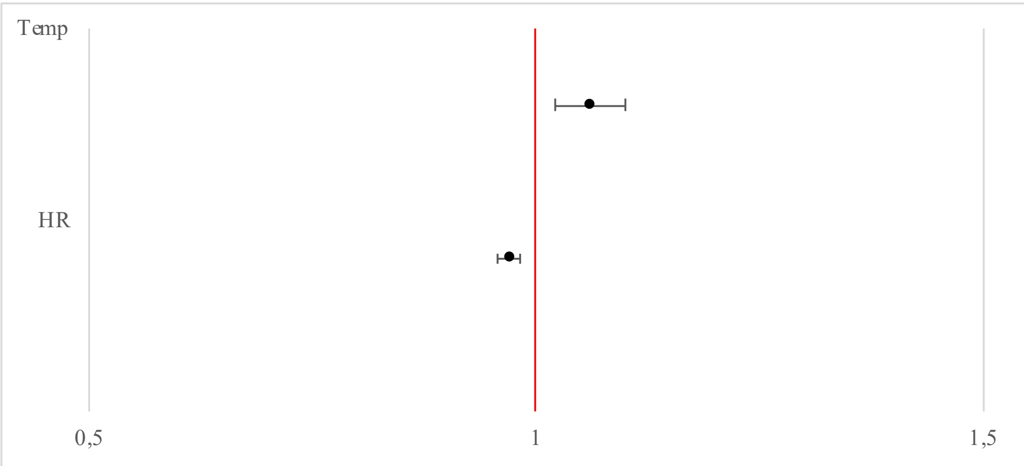


Figure 5.7: Odds ratios and 95% confidence intervals for IAQ

Figure 5.7, presents the odds ratios of Indoor air quality with a confidence interval of 95%. It is relevant, when interpreting these intervals that they don't predict values that cross the 1 axis (in red). Values greater than 1 mean that as the predictor variable increases, so do the odds of Indoor air quality, while values less than 1 mean the opposite.

Although IAQ is characterized by the CO_2 concentration, the response to the survey question *"At this time, do you find that ventilation or air quality is adequate?"* is not related to CO_2 concentration, rather it is related to indoor temperature and relative humidity.

5.2.5 Acoustic comfort

Multiple Linear Regression: Acoustic comfort

This model considers three measured predictors, The first model only considers the Airborne sound insulation of the façade, while the second includes Airborne sound insulation between spaces and Impact Sound Insulation (**Table 5.11**). R^2 of the second model is greater than the first, and all parameters are significant except the constant.

Table 5.11: *hierarchical regression of acoustic comfort*

	R^2	B	Std, dev,	t-value	Pr(>|t|)
Step 1	0,005				
Constant		2,44	0,12	19,521	<0,0001
Airborne sound insulation of façade		-0,18	0,005	-3,515	<0,0001
Step 2	0,036				
Constant		0,040	0,307	0,132	0,895
Airborne sound insulation of façade		-0,08	0,015	-5,250	<0,0001
Airborne sound insulation between spaces		0,047	0,011	4,505	<0,0001
Impact Sound Insulation		0,030	0,003	8,135	<0,0001

Binary logistic regression

Variables that were correlated with comfort vote on the linear regression were considered to develop a binary logistic regression. The BLR model found that only Ln was a significant predictor. The estimates for the BLR model are presented in **Table 5.12**, where only Ln is significant at 0,01.

The regression model for acceptable is presented in Eq. 5.7:

$$L_{NSV} = -2,010 - 0,03*d \qquad \text{Eq. 5.7}$$

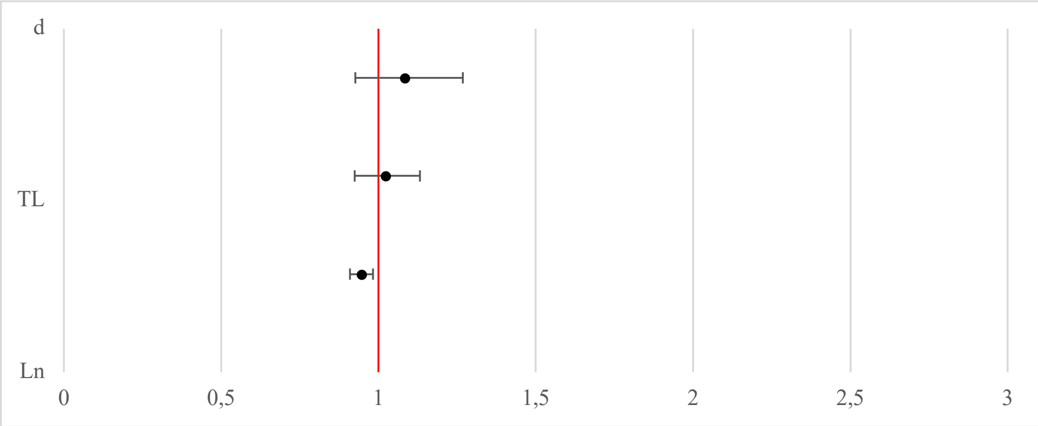


Figure 5.8: Odds ratios and 95% confidence intervals for acoustic comfort

Figure 5.8 presents the odds ratios of acoustic comfort with a confidence interval of 95%. It is relevant to note that the odds of Airborne sound insulation of façade (d) and Airborne sound insulation between spaces (TL) of predicting the outcome cross the 1 axis (in red). Values greater than 1 mean that as the predictor variable increases, so does the odds of acoustic comfort, while values less than 1 mean the opposite. The odds ratios presented in **Figure 5.8** show that only Ln gives us confidence that the direction of the relationship observed is true.

Table 5.12: Binary regression estimates for AV: acoustic vote

VARIABLE	Estimate	SE	P-value
(intercept)	4,191	1,627	0,010
D	0,079	0,079	0,320
TL	0,021	0,051	0,680
LN	-0,055	0,019	0,004
GOODNESS-OF-FIT: AIC: 807,4, DEVIANCE : 799,4 , NULL DEVIANCE: 824,5			

5.3 Discussion

In this chapter, a methodology to develop an index for IEQ is proposed. The methodology uses different statistical analyses to derive, firstly a general index of IEQ and then to characterize the parameters that influence the thermal, acoustic, visual and air quality sensation.

The general index of IEQ was constructed through Principal Component Analysis. An exploratory data analysis technique for reducing the dimensionality of a dataset while preserving the maximum amount of information.

The survey used to define the index had different scales for each question about sensation. This meant that a 'comfortable' vote for acoustic had a value of 1, while a 'comfortable' vote for thermal was 4. This presented several problems for the data analysis and meant that the index constructed gave weight to each factor but is not able to predict the evaluation of general comfort from the votes for each aspect.

The resulting index gave more weight to acoustic sensation, followed by IAQ and Thermal sensation, with a neglectable weight to visual sensation. If compared with one existing index for university classrooms (Buratti et al., 2018) acoustic sensation is much more relevant in this research. While in Buratti's index, thermal, visual, and acoustic parameters have similar weights.

The results of the characterization of the parameters that influence the thermal, acoustic, visual and air quality sensation are:

Indoor temperatures in the surveyed classrooms range from 13,1ºC to 23,9ºC. The comfort temperatures for children in classrooms in Coyhaique calculated with the proposed model are:

- 90% of acceptability with temperatures between 16,56°C and 22,27 °C.
- 80% of acceptability between 15,27°C and 25,27°C.

These comfort temperatures are low when compared with the recommendations in standards ASHRAE 55 and EN 16798. As stated by Teli (2012) this could be related to higher metabolic rates in children.

At a national level, the results can be compared with the findings of Trebilcock et al. (2017b) for Chilean students' primary schools in Santiago. That research presented lower comfort temperatures than the ones calculated for Coyhaique. In Santiago, the mean comfort temperature in winter was calculated as 14.6ºC when using the same method compared with 18,9 ºC for Coyhaique.

There are several differences between both case studies. Firstly, the climate of both cities is different, where Coyhaique has colder winters than Santiago. Secondly, the schools studied in Santiago were free running while all schools in this research were heated. The third difference could be the schools in Santiago had “vulnerable students” meaning that they came from families with lower living conditions and possibly did not heat their houses. For the case of Coyhaique, no information was provided to characterize the vulnerability of the students.

Since Coyhaique has a colder climate than Santiago and heating is needed in all types of buildings, it could be argued that students’ expectations for thermal comfort would be higher based on their experiences at home. While at the same time, the range of neutral temperature, of 5,71ºK for 90% of acceptability and 10ºK for 80% of acceptability, demonstrates that adaptation is occurring.

The evaluation of the IAQ vote against measured parameters shows that the occupants’ perception doesn’t correlate with CO_2 concentrations. On the other hand, IAQ sensation is correlated with indoor temperature and relative humidity. Although CO_2 is a recognized marker for IAQ, this research shows that it is not a marker for the sensation of ‘enough ventilation’.

Acoustic comfort was studied against measurements of the acoustic insulation of the envelope. There was a correlation between the insulation of the façade and acoustic sensation vote.

Coinciding with Humphreys (M. A. Humphreys, 2005b), this research does not provide proof of the universality of the index, Furthermore, the researchers are cautious of its applicability and suggest evaluating it against other school classrooms in other locations.

5.4 Limitations and suggestions for future work

The main limitation of this work is the quality of the gathered data, Real-world external events, prevented the researcher to access classrooms and gathering data that would have enriched the index. However, the amount of data available sufficed to develop a methodology. The initial results indicate that it would be interesting to further develop this index, once school classrooms are back in operation.

The lack of information about the use of artificial lighting and illuminance levels inside the classrooms meant it was impossible to build an index.

Considering the high contamination of the air in the winter months in Coyhaique further research should also measure it inside the buildings. Since the buildings only had natural ventilation, contaminated air can be assumed based on outdoor conditions.

To better the predictability of the index, it is advised to include the measurement of maximum sound pressure level (Lmax) for predicting comfort with impact noise, and equivalent sound pressure level (Leq). As well as Luminance and glare should also be measured in tandem with information about light sources.

6 Survey development

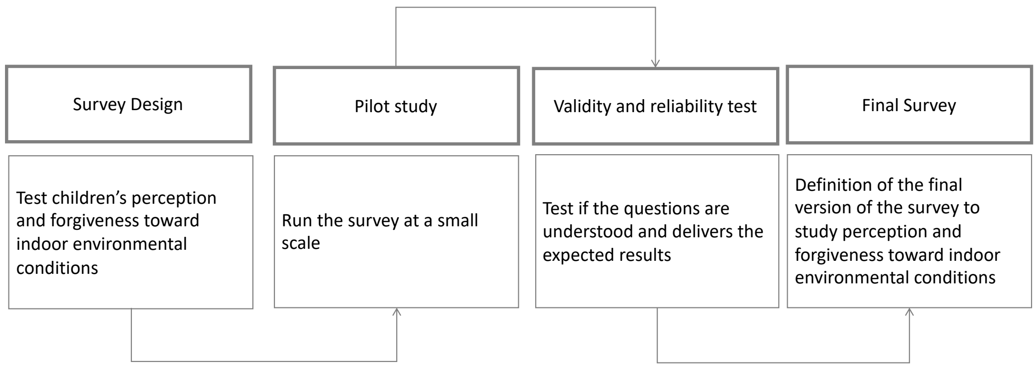
This chapter presents the development and validation of a survey and the data collection protocol developed for the observational part of the study. Based on the literature review presented in Chapter 2, a need for a new comprehensive survey was found as well as the need to adapt it to the language and cognitive abilities of school students.

This survey was developed to answer research question 2, as well as proposing a tool to gather data to answer question 3:

5. *"What are the relationships between the thermal, acoustic, light and air quality conditions and requirements and the perception of IEQ from the perspective of school students in Chile?"*
6. *What is the perception of the environmental comfort of the students in their classrooms?*
7. *What is the relevance given by students to each parameter of IEQ?*
8. *Under which conditions will students be forgiving of the IEQ?*

The conceptual study framework of this chapter is shown in **Figure 6.1**. This graphic represents the mains steps of the research workflow

Figure 6.1*: Study methodological framework*



6.1 Introduction

Students' comfort perception has been linked with performance (Bakó-Biró et al., 2012; M. J. J. Mendell & Heath, 2005; Porras-Salazar, 2018; Roebuck, 2020; Stafford, 2015; Vakalis et al., 2020; Wargocki et al., 2017, 2019, 2020b), health (Baloch et al., 2020; Chatzidiakou et al., 2014; Elbayoumi et al., 2015; Jones et al., 2007; Klatte & Hellbroock, 2010; Madureira et al., 2012; Magzamen et al., 2017; Turunen et al., 2013; Van Dijken et al., 2006), and wellbeing (Klatte & Hellbroock, 2010; Turunen et al., 2013). Therefore, it is vital to know how they perceive their learning environments as one of many tools to diagnose possible ways to improve their performance and wellbeing. Since children have different metabolisms, development, and point of view as adults, it is relevant to enquire them directly instead of relying on their teachers' perception.

Most of the existing surveys to evaluate Indoor Environmental Quality have been developed in industrial countries to be applied to Post Occupational Evaluation (POE) of office buildings **Table 6.1**. Some relevant examples of this survey are the BUS occupant survey, which was developed in the UK for benchmarking office buildings against an ever-growing database of case studies (Leaman & Bordass, 2001). The CBE survey, developed by the Centre for the Build Environment in Berkley (Frontczak et al., 2012) consists of a toolkit with an occupant satisfaction survey and a scorecard report generation tool (Zagreus, Huizenga, et al., 2004) and has been applied in more than 600 buildings (Galatioto et al., 2014). The HOPE study (European Health Optimisation Protocol for Energy-efficient Buildings) developed a comprehensive survey of the perceived state of health and comfort by the occupants of office buildings (P. M. Bluyssen et al., 2011) However, in the literature review (Chapter 2) no validated surveys of IEQ in classrooms specifically designed to answer questions about the weight that each parameter of IEQ has on the general perception of comfort were found.

Some considerations must be made when surveying children. In the past, Humphreys studied the ability of schoolchildren to understand and vote on a thermal comfort rating scale (M. A. Humphreys, 1977a). He found that less than half the seven-year-old children were capable of understanding a simply worded thermal sensation scale, around half of the 8-year-old could do so, while most of the 9-year-old did understand and correctly respond to the thermal sensation scale. Teli (2013) used discrepancies between TSV and TPV to assess the comprehension of her simplified thermal comfort survey by children. They found a 7% of discrepancies among the whole sample of 7 – 11-year-old students. The low discrepancies were interpreted as the capability of understanding simplified thermal sensation and preference rating scales (Teli et al., 2013). Other researchers have developed surveys, most of them to evaluate thermal comfort (Auliciems, 1969; R. de Dear et al., 2015; Haddad et al., n.d.; Kim & de Dear, 2018; Trebilcock et al., 2014). But a lack of questionnaires to evaluate IEQ designed for children has been identified. Therefore, a new survey considering thermal, acoustic, and visual comfort plus indoor air quality was developed and validated considering the developmental stage of school children.

6.2 Methodology

The design and validation of this survey were made according to the scheme in **Figure 6.2** Special attention was given to the posterior statistical analysis of the results. Therefore, the questions and the possible responses were designed to gather data about the perception of environmental comfort and the relevance given by students to each parameter of IEQ.

The questions about the validity and reliability of the survey are relevant when designing a new instrument (Boynton & Greenhalgh, 2004). The methods used to verify the reliability of the survey were pre-testing or piloting the survey while using observation forms, cross-checking responses to measurements and applying different statistical analyses.

This part of the PhD is defined as a modelling study because the focus is not on the results of applying the survey, but on how to acquire the information needed.

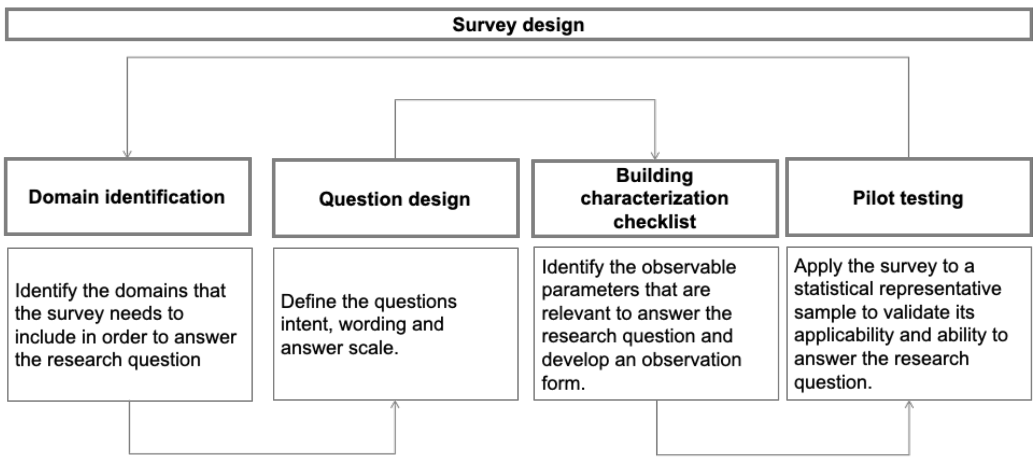


Figure 6.2: *Survey design methodological framework*

Some materials have been removed from this electronic version of the dissertation.

The unabridged version of the thesis will be made available as soon as possible at this same location.

6.4 Discussion

Factorial analysis of the survey demonstrated that respondents identified one domain that included thermal, acoustic, visual and air quality acceptability. Questions about sensation were not clearly correlated with the measured parameters. This could be related to the more complex wording of the questions or the age of the respondents (10 to 13-years-old). Previous research (Korsavi & Montazami, 2019a; Mors et al., 2011; Teli et al., 2012; Trebilcock et al., 2014) found that children were able to respond to sensation questions for indoor temperature. Contrarily, the analysis of this survey does not confirm previous findings. Furthermore, the responses to questions about acoustic, visual and air quality sensation were not correlated with measurements.

Therefore, it is decided to only maintain the questions about acceptability. This question was worded straightforwardly, and the possible answer is a Likert-scale, as sensation. The final version of the survey 'IEQ-F-2' is available in ***Annex 4***.

6.4.1 Strength and limitations

The proposed survey was validated with a sample of n=106 responses in a school building located in Concepcion, Chile. Before the development of this survey, no instrument to evaluate the IEQ of school children was found, therefore the present survey is an innovative contribution to the field of IEQ evaluation.

Due to the constraints of the COVID-19 pandemic, it was not possible to use the survey to evaluate IEQ in a bigger sample within the timeframe of this dissertation. Further application of the tool is advised.

6.4.2 Future work

This study represented the first survey developed to evaluate the Indoor environmental comfort of children inside their classrooms to find conditions when they are more forgiving of their environment. The validated survey IEQ-F-2 is a reliable and validated survey, which results permitted the identification patterns of forgiveness between respondents.

Future research should address the topic of forgiveness through bigger datasets to define an equation able to describe the phenomenon. Considering the many environmental factors that would affect the proposed forgiveness, the further scaling of this research should consider a sample that can control for outdoor conditions.

6.5 Conclusions

The results of this study demonstrate that IEQ-F-2 survey is a validated and reliable tool to evaluate the indoor environmental comfort of children in classroom settings and to evaluate the weight given to each parameter on their overall comfort.

This tool provides designers and school operators with relevant data from the occupant's point of view. This survey can also orientate decision-making for the renovation of existing buildings, where the comfort of the children is the aim.

7 Development of the Index

This chapter presents the development of an index that summarizes the evaluation of Indoor Environmental Quality (IEQ) from the perspective of students in school classrooms. The main objective of this research is to propose a methodology for the definition of a weighted environmental comfort index for primary schools, based on the study of environmental comfort and the corresponding environmental variables. In this sense, the statistical analysis of the data will allow pairing measured variables with the comfort perception of the students, while also describing this correlation.

This index is based on the acceptability vote for the four main aspects of IEQ, namely: thermal, acoustic, visual, and air quality. The index is developed based on the results of the application of the survey developed in Chapter 6.

This index was developed to answer research questions number three of this research:

1. "What are the relationships between the thermal, acoustic, light and air quality conditions and requirements and the perception of IEQ from the perspective of school students in Chile?"
2. What is the perception of the environmental comfort of the students in their classrooms?
3. What is the relevance given by students to each parameter of IEQ?
4. Under which conditions will students be forgiving of the IEQ?

The conceptual study framework of this chapter is shown in **Figure 5.1**. This graphic represents the main steps of the research workflow.

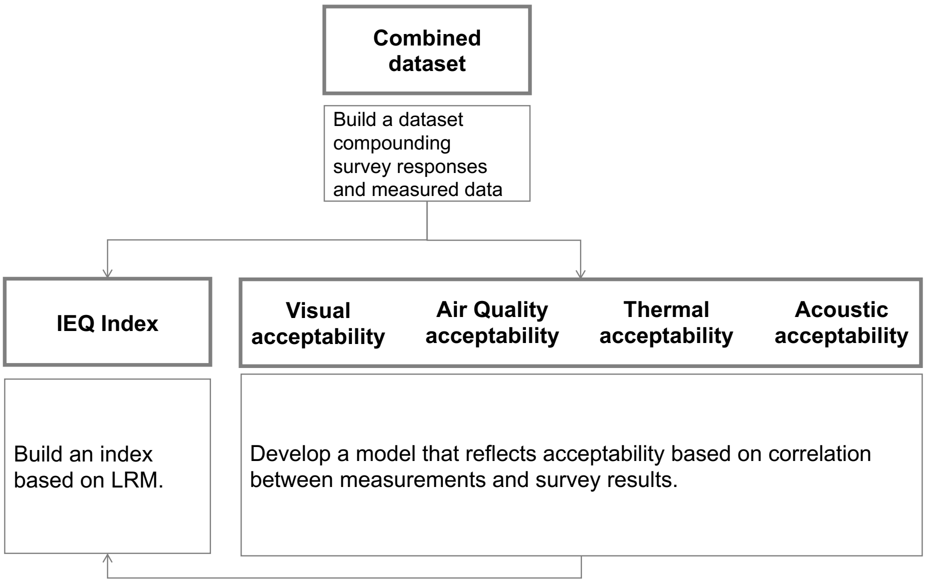


Figure 7.1: *conceptual study framework for the development of an index*

The key objective is to first identify the parameters that define comfort for the users, and then propose a weighting of these parameters to devise a multi-criteria and holistic index of IEQ.

This PhD aims to develop an indicator that will allow **weighting of the relevance of the four aspects of IEQ**, concerning the general comfort of students in school classrooms, allowing the evaluation and comparison of the quality of the spaces. This part of the research responds to the following research objectives:

- Design a methodology that allows weighting in a single index of the environmental factors to predict the environmental comfort of children-occupants of school classrooms.
- Define the indoor environmental conditions under which students will be forgiving of the IEQ.
- Validate the proposed methodology and explore its applicability.

7.1 Conceptual definition of an index

A basic definition of the Index would consider thermal comfort (I_T), visual comfort (I_V), acoustic (I_A), comfort and indoor air quality (I_{IAQ}), and normalize them:

$$I_{IEQ} = \frac{I_T + I_{IAQ} + I_V + I_A}{4} \qquad \textit{Eq. 7.1}$$

Such an index has been described by Catalina and Iordache (Catalina & Iordache, 2012), as presented in Table 2.5. The main problem found in the literature with this definition of an index is that the equation does not consider that some people will give more prominence to one aspect of IEQ than others. To address this, the equation needs to be updated to include different weights for each aspect by including one coefficient for each of them:

$$I_{IEQ} = \frac{(I_T * C_T) + (I_{IAQ} * C_{IAQ}) + (I_V * C_V) + (I_A * C_A)}{4}$$	*Eq. 7.2*

The coefficients presented in Eq. 7.2 represent the weight that the children-occupants of school classrooms give to each aspect when they evaluate them through a validated survey (Chapter 6). It is relevant to note the difference between seemingly equivalent concepts, as described more in detail in Chapter 2. The proposed Index presents a multi-criteria evaluation of IEQ, that correlates with the environmental sensation reported by the respondents. The cross-modal effects, as well as the interactions between parameters, are not considered in the design of the Index.

Indexes that use the same base equation are summarized in **Table 2.5**, where the weight given to each of the coefficients are described. Five of eight of the indexes give more weight to the thermal environment, while air quality seems to be one with less weight. The variability in the weight given in each index was discussed by Humphreys (2005a) who acknowledges that "not all aspects are equally important in this subjective averaging process". In this sense, expectations play a relevant role. Many factors can shape the expectations of the occupants. In the same text, Humphreys proposed that culture would be key in defining such expectations.

Based on the results presented in paper 1 (Diaz, Cools, et al., 2021) and Chapter 5, exposure to different environmental conditions can also have an impact on expectations. As discovered when comparing thermal comfort for students in Santiago, Puerto Montt and Coyhaique, were the latter has a higher comfort temperature than the other two cities. These results are contra-intuitive, as Coyhaique has the lowest outdoor temperatures during the surveyed period. The explanation for these differences is that indoor temperatures are higher in Coyhaique, as heating is a necessity. It is also hypothesized that children are exposed to higher indoor temperatures at home in Coyhaique, this hypothesis coincides with the study of Trebilcock et al. (2017b) that relates lower thermal expectation with higher economic vulnerability.

In her PhD research, Pierson highlights the socio-environmental context and defines it as “the climate and habitat, including indoors and outdoors, to which a subject has been acclimatized, her/his behaviour towards these elements, and her/his expectations about them” (Pierson, 2019, p. 114).

The expectations are also dependent on the intended use of a building, schools, hospitals, and music venues will present different expectations to their occupants. Therefore, part of the variance in weight in the indexes presented in table **Table 2.5**, could be attributed to different types of buildings.

Therefore, the need for a multi-criteria and holistic index developed to predict the Indoor Environmental comfort of school children in Chile appears.

Table 7.1: *Values given to each coefficient in the literature and method used to develop the index. Based on* (Leccese et al., 2021)

	thermal CT	***air quality CIAQ***	***acoustic CA***	***visual CV***	***method***
Astolfi and Pellerey (2008) [a]	0,33	0,21	0,26	0,2	PCA
Cao et al. (2012) [a,c]	0,38	0,14	0,27	0,21	MvLR
Lee et al. (2012) [a]	0,22	0,18	0,39	0,21	MvLgR
Catalina and Iordache (2012) [a]	0,25	0,25	0,25	0,25	MNLR
Ghita and Catalina (2015) [a]	0,27	0,3	0,19	0,24	-
Thasildoost and Zomorodian (2018b) [b]	0,34	0,09	0,26	0,31	PCA
Buratti et al. (2018) [b]	0,35	--	0,35	0,3	PCA
Fassio et al. (2014) [b]	0,33 [x]	0,10 [x]	0,18 [x]	0,38 [x]	MvLR
Leccese et al.,(2021) [b]	0,43	0,17	0,16	0,24	MvLR
Average	0,3	0,2	0,26	0,24	

[x] different weight depending on time of the survey. 11:30 is presented.
[a] school classroom, [b] university classroom, [c] Public/office building
PCA: Pearson Correlation Analysis, MvLR: Multivariate Linear Regression, MvLgR: Multivariate Logistic Model AHP: Analytic Hierarchy Process.

Some materials have been removed from this electronic version of the dissertation.

The unabridged version of the thesis will be made available as soon as possible at this same location.

8 Conclusions and future work

This chapter presents the general discussion and conclusions of this PhD thesis. It summarizes the original contributions developed in this PhD thesis and provides recommendations for future research.

8.1 Discussion

Indoor environmental quality is a multi-criteria indicator that refers to indoor conditions in a building related to the health, productivity, and wellbeing of those who occupy it. Several definitions exist, while the most common include thermal, acoustic, visual, and air quality as indicators. Other indicators that have been included are spatial and psychosocial factors.

In schools, the relevance of the perception of IEQ is highlighted by the time spent inside the classroom and the detrimental effect that poor IEQ can have on learning. The literature review demonstrated that the built environment affects children's attention, performance, and school attendance. Although, it should be considered that his effect is limited, and other factors like socio-economic factors, family of origin, quality of the teachers, and others have a greater impact on learning. Nevertheless, it is relevant to provide the necessary Indoor environmental quality to foster learning at school and make it a place of wellbeing.

The review made in ***Chapter 2*** indicated that there is a need to better understand how IEQ is defined by the occupants based on their evaluation of thermal, acoustic, visual, and air quality. Although environmental stimuli are perceived simultaneously, researchers have isolated thermal, acoustic, visual, and air quality to better understand and evaluate them. But if the aim is to evaluate the IEQ as a whole, there is a need for an indicator that combines these factors.

Chapter 4 presents an exploration of the effects that environmental factors, as well as climatic conditions and seasons have on the concentration of CO_2 in school classrooms. Dealing with the research question *'What are the relationships between the thermal, acoustic, light and air quality conditions and requirements and the perception of IEQ from the perspective of school students in Chile'*. This chapter only considers air quality parameters to simplify the problem and study if there are crossed effects that affect the perception of IAQ. The study found that: The climatic conditions are a differentiating factor for CO_2 concentrations. In this case, there is a statistically relevant differentiation between CO_2 concentrations in Santiago and Puerto Montt, where both cities have distinct climates. Another finding was that acceptable CO_2 concentrations are determined by seasonality, increasing the chances of desirable CO_2 concentration (below 1000 ppm) in spring over winter. Lastly, it was found a crossed effect where the indoor temperature is a relevant factor in predicting CO_2 concentrations. Further study on this effect was done in ***Chapter 5,*** where it was found that not only CO_2 concentrations are correlated with temperature, but the perception of IAQ is correlated with indoor temperature and relative humidity.

Based on the literature review and building on previously developed indexes, ***chapter 3*** presents a methodology to build an IEQ index that weights the thermal, acoustic, visual, and air quality parameters against the general acceptability of the indoor environment. This methodology is applied to an existing dataset collected for a POE of classrooms in the southern city of Coyhaique in Chile to create an index that reflects the evaluation of IEQ by the school students. The resulting index considered the thermal, acoustic, light and air quality conditions. In this case, the noise had a higher weight followed by IAQ, temperature and light perception as shown in Eq 6.1.

$$Ind_{Conf} = 0{,}55 \times NSV + 0{,}48 \times IAQ - 0{,}47 \times TSV - 0{,}02 \times VSV \qquad \text{Eq. 6.1}$$

One of the downsides of the developed index is that the dataset did not include data on the general acceptability of the indoor environment, making it difficult to contrast the vote for each factor with the general perception. Therefore, a new validated survey was needed.

The literature review presented in ***Chapter 2*** found that there are no validated tools to evaluate IEQ from the perspective of school children in their classrooms. The surveys found in the review were developed for the evaluation of IEQ in office buildings as part of POE or adapted for school children to study thermal comfort and adaptation. Thus, in ***Chapter 6***, a new survey was developed and validated. This new survey was designed with questions adapted to the language and cognitive development of children 10 to 13-years-old. The validation of the resulting survey found that questions about sensation were not clearly correlated with the measured parameters. This could be related to the more complex wording of the questions or the age of the respondents (10 to 13-years-old). While factorial analysis of the survey demonstrated that respondents identified one domain that included thermal, acoustic, visual and air quality acceptability. The questions about acceptability were worded straightforwardly, and the possible answer is a Likert-scale.

The final version of the survey accompanied by the building characterization checklist are a novel tool that provides designers and school operators with relevant data from the occupant's point of view. This survey can also orientate decision-making for the renovation of existing buildings.

Chapter 7 presents the development of an index that summarizes the evaluation of Indoor Environmental Quality (IEQ) from the perspective of students in school classrooms. Using the survey developed in the previous chapter and using the acceptability vote for the four main aspects of IEQ as predictors. This index was developed through multiple linear regression and found that the most relevant aspect of IEQ was air quality, followed by noise and temperature, with a neglectable influence of lighting (Eq. 7.4).

$$I_{IEQ} = 0{,}47\text{AAV} + 0{,}22\text{NAV} + 0{,}16\text{VAV} + 0{,}15\text{TAV} \qquad \textit{Eq. 8.2}$$

When compared with previously developed indexes in the literature, all reviewed studies (**Table 2.5**) gave preponderance to the thermal aspect. Since thermal comfort has been described as the most important of the variables of IEQ (Frontczak & Wargocki, 2011), although this idea is challenged by the results of this research. One possible explanation is related to the newfound value of ventilation. Students were aware that increasing ventilation flow had a side effect of lowering the indoor temperature, and therefore lowered their expectations to favour ventilation.

These results are thought-provoking, since they reflect the impact that expectations can have on the evaluation of IEQ. The presumption of what 'good IEQ' is depends on various factors. As mentioned in ***Chapter 5,*** previous experiences, climatic adaptation, and even socioeconomic status can affect it. From these results, it is possible to hypothesize that expectations can change if there is a logic to it. In this case, the indoor temperature is less relevant because the occupants understand that during the pandemic having more ventilation will reduce their risk of infection.

The results of the developed index can be applied to understand how children perceived the environment during de COVID-19 pandemic. From the weight given to each parameter, it is clear that children give much more relevance to the air quality than other aspects of the indoor environment. This information can help to decide where to invest in a refurbishment. From the perception of the students, we can suggest investing in bettering indoor air quality, either by architectural design or by using active strategies. This change should have a bigger impact on general acceptability.

From a methodological point of view, the index development shows that it is possible to evaluate the acceptability of the general environment in terms of the acceptability of thermal, acoustic, visual and air quality environment. Although some of the variability is still not accounted for. The developed methodology could be applied to other case studies to evaluate the perception of IEQ in existing school buildings.

Lastly, the results of the developed index can guide the design of new schools aiming to have better overall comfort.

The weight given to each aspect of IEQ can be used as a tool to prioritize the investment in building renovation.

This adaptation to changing IEQ expectations could be further studied as a way to cope under other circumstances. For example, lower indoor temperatures to respond to higher fuel prices or to lower the environmental impact of heating.

When further studying the changes in expectations, the period of time in which these 'new expectations' are acceptable should be considered. It is very possible that occupants will not withstand these conditions for longer periods of time if they think that changes could be made to improve them. In the current research design, it's not possible to validate this hypothesis.

8.1.1 Thermal comfort

Thermal comfort has been described as the most important of the variables of IEQ (Frontczak & Wargocki, 2011), and many of the indexes found on the review, had it as the most weighting parameter. All schools in this research presented low temperatures outside the thresholds defined for occupied periods. At the same time, the evaluation of acceptability and thermal comfort did not match the requirements set by international standards. This research supports the need for defining a standard adapted to the expectations of the occupants, while at the same time ensuring an optimal environment for health and productivity. Current knowledge is not consistent on the effects of lower temperatures in classrooms (between 20 ºC and 17ºC) on performance. At the same time, the benefits to the energy efficiency of buildings and the country of maintaining winter temperatures in this range should encourage investment in this line of research.

The results of the three case studies did not match the requirements of thermal comfort nor standards for indoor temperature set by standards designed for healthy adults in office settings. This factor should also be considered when studying the possible applications of lower comfort temperatures in school classrooms.

8.1.2 Indoor air quality

Indoor air quality is currently a concern of the occupants of school classrooms due to the relevance given to this factor during the COVID-19 pandemic. It is advised to maintain the interest in IAQ, considering the impact it has on productivity, and absenteeism in schools.

The main factors that should be considered are high occupant density, lack of ventilation design or ventilation systems, and lack of regulation, all of which are systemically related to bad IAQ.

Chapter 4 demonstrated that the variability of CO_2 concentrations is dependent on seasonality and indoor temperature. The results of this research do not support the claim that occupants can feel and react to bad IAQ. Therefore, systems should be in place to either inform on bad IAQ to encourage behaviour or ensure the needed air change.

It should be considered that over-ventilation has impacts on energy use and indoor temperatures. Therefore, actions to ensure proper ventilation should be selected through a systemic approach.

The results in chapter 7, should not be taken as a sign of betterment. These results are representative of very unusual conditions with lower occupancy density and over-ventilation. The results of this research cannot predict if IAQ will be maintained during the full occupation, even if over-ventilation is in place.

8.1.3 Visual Comfort

Visual comfort was the least relevant aspect of IEQ in both studies that included it. It is possible that the access to natural light provided by the normative requirements makes it a given for the occupants. Nonetheless, glare was present in most classrooms especially on the whiteboard.

8.1.4 Acoustic comfort

There is no definitive definition of acoustic comfort

- Noise can be generated indoors or outdoors, and different strategies need to be used to control it.

No correlation between acceptable acoustic conditions and the surveyed aspects was found. The same was true for the measured L_{eq}. Considering the special conditions during the COVID-19 pandemic, one possible explanation is the lack of variability in indoor acoustic conditions. During the measured period, between 2 and 7 children were present in the classroom, while the remaining were connected online to the class. Therefore, there was little noise produced inside

8.1.5 Survey: Strengths and limitations

The proposed survey was validated with a sample of N-106 responses in a school building located in Concepcion, Chile. Before the development of this survey, no instrument to evaluate the IEQ of school children was found, therefore the present survey is an innovative contribution to the field of IEQ evaluation.

Due to the constraints of the COVID-19 pandemic, it was not possible to use the survey to evaluate IEQ in a bigger sample within the timeframe of this dissertation.

8.1.6 Regulations and standards

The regulations that define the design of classrooms in Chile is prescriptive. As the term suggests, these regulations stipulate precisely what must be done to meet certain safety and environmental standards. As this research shows, there is no clarity of what the standards are for thermal comfort, air quality, natural lighting, and acoustic comfort. Only the standards for artificial lighting are clearly defined. All classrooms studied comply with the regulations, but still, they leave little room for interpretation and provide clear instructions on how to achieve compliance. Worldwide, regulations are aiming at defining thresholds that need to be met. This type of regulation, in the case of environmental comfort means that some parameters should be monitored to ensure that they comply with the required threshold. Taking as an example thermal comfort, this research has shown that the threshold for thermal comfort of children differs from adults and that the range of temperatures where they feel comfortable is wither than suggested y the literature. Therefore, there is a need for defining new thresholds for IEQ. The proposed methodology if applied to a big sample correcting for diversity in climate, age, and culture, would allow to define such thresholds.

8.1.7 Architectural design of classrooms

The approach to designing schools for indoor environmental quality should adopt a comprehensive viewpoint. Particularly in the global south, adopting a passive design approach proves highly beneficial, not only for minimizing operational costs, energy dependency, and maintenance but also enhancing the resilience of buildings against natural disasters (Trebilcock, Soto, et al., 2016).

Strategies related to Indoor Environmental Quality (IEQ) will have distinct effects on acoustic, visual, thermal comfort, and indoor air quality. Consequently, these strategies will be categorized based on their location within the room.

Climate is pivotal when designing energy-efficient buildings, especially in the context of the current climate emergency. Considering the extended lifespan of schools, future climate scenarios must also be taken into account. Climate change affects heating and cooling loads, rainfall patterns, and sky coverage. Microclimate characteristics, such as topography, waterbodies, urban heat islands, and vegetation, play a crucial role and can be manipulated to influence the surrounding conditions.

Heating and cooling loads are contingent on local climate conditions, and tools like cooling degree days and heating degree days can be used to assess them. Additionally, factors like pluviometry, daily temperature changes, solar radiation, wind, and humidity impact thermal comfort. Noise from external sources, such as roads and airplane routes, should be identified and factored into the building envelope design.

Walls constitute a significant portion of classroom envelopes, influencing both interior aesthetics and exterior climate interactions. Key considerations include wall insulation, which impacts both thermal and acoustic aspects. Proper selection of insulation materials is crucial for minimizing heating and cooling needs. The thermal mass of walls can be utilized to regulate temperature variations, and finishes, including color and materials, affect light perception and acoustic quality.

Windows, designed for natural light and ventilation, are influenced by climate parameters. Window orientation, ventilation patterns, size, material, outside view, and shading all contribute to overall IEQ. The preferred window position is often determined by climate conditions, considering factors like sunlight, wind, and noise. Ventilation strategies, including cross-ventilation and solar chimneys, are essential for ensuring good indoor air quality. Window size and design must balance natural light distribution and glare potential. The choice of window materials impacts thermal and acoustic performance.

Roofs, as the fifth façade, can impact IEQ. Material selection should align with the climate, and considerations for thermal mass and insulation are essential. Green roofs can serve as additional outdoor spaces, providing benefits associated with contact with nature.

Floor design affects thermal, visual, and acoustic comfort. Considerations include colour, finish, and material selection to prevent glare, maintain thermal comfort, and enhance acoustic insulation.

Furniture design, including colour and finish, plays a role in preventing glare and enhancing light distribution. Reflection considerations are crucial for maintaining a comfortable learning environment.

The design of school classrooms should be informed by the expectations of the users.

8.2 Conclusions

The hypothesis that students will be more indulgent (or forgiving) with certain aspects of IEQ while other thresholds are met was confirmed by the results of Chapter 7. There, it was found that occupants lowered their expectations in favour of higher ventilation rates. Therefore, the first null hypothesis has been rejected.

The aim defined for this research was to develop an indicator that will allow **weighting of the relevance of the four aspects of IEQ**, concerning the general comfort of students in school classrooms, allowing the evaluation and comparison of the quality of the spaces. Chapter 7 presents the development of such an index, but with limited representativity. The constraints posed by the COVID-19 pandemic delayed the monitoring and surveying campaign and hindered the evaluation of all the case studies.

Research objective 1 meant to determine the relationships between the thermal, acoustic, light and air quality parameters and requirements and the IEQ for students within the classrooms and delineate an index. This part of the study was accomplished in Chapter 2, which presents the review of previous research. Based on those results, the interactions between parameters were studied in Chapter 4, which presents the effect that indoor temperature and seasonality have on IAQ characterized by the indicator of CO_2 concentration. Parameters and requirements were studied in chapter 2 and are contrasted against the results of this study in chapter 7.

The evaluation of the environmental conditions and the perception of the environmental comfort of the students in educational establishments to weigh the relevance of each parameter on the index was established as the research objective 2. From the results of Chapters 4 and 5, appeared the need to develop a tool to gather relevant information to answer this objective. After developing this tool, this objective was reached by the evaluation made in Chapter 6.

The design of a methodology that allows weighting in a single index of the environmental factors to predict environmental comfort was done in Chapter 7. The results of this chapter demonstrated that the methodology is valid, although the results are not extrapolated to other school classrooms. Mainly because the study was done under the conditions of the return to classes after the pandemic.

The last objective of this research focused on understanding the indoor environmental conditions under which students will be forgiving of the IEQ. The results presented in chapter 7, demonstrate that occupants are forgiving and hint at a relationship between expectations and forgiveness. Further research is needed to clearly state this relationship. The available means in this research do not permit performing an experiment to corroborate this claim.

8.3 Future work

After answering the research questions formulated for this research, new questions emerged during the development of the project.

- The developed survey to evaluate the Indoor environmental comfort of children inside their classrooms is a reliable and validated survey, which results allowed to identify patterns of forgiveness between respondents. But future research should address the topic of forgiveness through bigger datasets to define an equation able to describe the phenomenon.

- Considering the many environmental factors that would affect the proposed forgiveness, the further scaling of the use of this survey could consider a sample that can control for outdoor conditions.

- Due to the constraints posed by the COVID-19 pandemic, the monitoring and surveying were done in classrooms with lower attendance and lower occupant Density. This affected CO2 production, smells, indoor temperature, humidity, and equivalent continuous sound level. Therefore, an evaluation under typical use conditions should present different results for both measured parameters and IEQ evaluation.

- The low variability of, for example, equivalent continuous sound level (L_{eq}) meant that no statistically significant model was found to describe the probability of an acceptable acoustic environment. The methodology to build the index should be applied to other cases studies or under experimental conditions.

- The adaptation to changing IEQ expectations, found in **Chapter 7** could be further studied to cope under other circumstances. For example, lower indoor temperatures to respond to higher fuel prices or to lower the environmental impact of heating.

- When further studying the changes in expectations, the period of time in which these 'new expectations' are acceptable should be considered. It is very possible that occupants will not withstand these conditions for longer periods of time if they think that changes could be made to improve them.

- Our dataset needs to be expanded to increase the representativeness of the sample on the national and international levels. The sample should allow for climate-based clustering to represent schools in cooling-dominated climates and mixed climates, such as Iquique and La Serena.

- After developing the index, there still is part of the variability that is not accounted for. Therefore, other variables could be included in the model. The current research does not provide clues to identify those variables.

- Further research is needed to clearly state the relationship between expectations and forgiveness. This question could be answered by an experiment to corroborate this claim.

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Appendix A: Published papers

Diaz, M., Cools, M., Trebilcock, M., Piderit-Moreno, B., & Attia, S. (2021). Effects of Climatic Conditions, Season and Environmental Factors on CO_2 Concentrations in Naturally Ventilated Primary Schools in Chile. *Sustainability*, *13*(8), 4139. https://doi.org/10.3390/su13084139

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Diaz, M., Gonzalez-Caceres, A., & Attia, S. (2023). *Multicriteria Design: Optimizing Thermal, Acoustic, and Visual Comfort and Indoor Air Quality in Classrooms* (pp. 435–449). https://doi.org/10.1007/978-3-031-24208-3_30

Annex 1

Survey used in Coyhaique casestudies

Genero	**Gender**
Nombre	Name
Curso	Grade
Colegio	School
Puesto en la sala	Position in the room

¿Cómo sientes la temperatura de la sala en este momento?	**How do you feel the temperature of the room at the moment?**
muy fría	very cold
fría	cold
un poco fría	a little cold
agradable	pleasant
un poco calurosa	a little warm
calurosa	hot
muy calurosa	very hot

haz un tick (✓) en la frase que te parece más apropiada	**tick (✓) on the phrase that seems most appropriate to you.**
Me gustaría que la sala estuviese mucho más fría	I would like the room to be much cooler
Me gustaría que la sala estuviese más fría	I would like the room to be cooler
Me gustaría que la sala estuviese un poco más fría	I would like the room to be a little cooler
Me gustaría que la sala estuviese igual	I would like the room to be the same
Me gustaría que la sala estuviese un poco más calurosa	I would like the room to be a little warmer
Me gustaría que la sala estuviese más calurosa	I would like the room to be warmer
Me gustaría que la sala estuviese mucho más calurosa	I would like the room to be much warmer

En este momento ¿sientes que la temperatura de la sala es aceptable?	**At this time, do you feel that the room temperature is acceptable?**
sí	yes
no	no

En este momento ¿estás usando tu chaleco o polerón del colegio ?	**Are you currently wearing your school vest or sweatshirt ?**
sí	yes
no	no

En este momento ¿estás usando tu parka, chaquetón o polar encima del uniforme?	Are you currently wearing your parka, jacket or fleece over your uniform?
sí	yes
no	no

¿qué actividad estuviste realizando antes de responder la encuesta?	What activity were you doing before answering the survey?
en clases, sentado	in class, sitting
en clases de educación física	in physical education classes
corriendo durante el recreo	running during recess
descansando durante el recreo	resting during recess

En este momento, ¿Qué tan fuerte es el ruido ambiental?	At this time, how loud is the ambient noise?
Nada ruidoso	Not loud at all
Ligeramente ruidoso	Slightly noisy
Medianamente ruidoso	Moderately noisy
Muy ruidoso	Very loud
Extremadamente ruidoso	Extremely noisy

En este momento, ¿Cuánto le molesta el ruido ambiental?	At this moment, how much does the ambient noise bother you?
Nada ruidoso	Not at all noisy
Ligeramente ruidoso	Slightly noisy
Medianamente ruidoso	Moderately noisy
Muy ruidoso	Very noisy
Extremadamente ruidoso	Extremely noisy

El ruido que usted siente proviene de:	The noise you feel is coming from:
Local vecino de su mismo piso	Neighboring premises on the same floor
Local vecino de otro piso	Neighboring premises on another floor
Equipamiento	Equipment
Exterior	Outside

En este momento, ¿Ud. Escucha y entiende bien las palabras y frases que el profesor pronuncia?	At this moment, do you hear and understand well the words and phrases that the teacher pronounces?
Nada	Not at all
Ligeramente	Slightly
Medianamente	Moderately
Bien	Well
Muy bien	Very well

En este momento, ¿Ud. Siente la presencia de corrientes de aire?	At this moment, do you feel the presence of air currents?
Si	Yes
No	No

La corriente de aire perturba su actividad o comodidad?	Does the draft disturb your activity or comfort?

Mucho	A lot
Poco	A little
Nada	Not at all

En este momento, ¿Ud. encuentra que la ventilación o calidad el aire es adecuado?.	**At this time, do you find that the ventilation or air quality is adequate?**
Muy de acuerdo	Strongly Agree
De acuerdo	Agree
Me es Indiferente	I am Indifferent
Desacuerdo	Disagree
Muy desacuerdo	Strongly Disagree

¿Por qué razones?	**For what reasons?**
Percibe aire viciado	You perceive stale air
Percibe aire caluroso	Perceives hot air
Percibe el aire frío	You perceive cold air

La iluminación sobre su escritorio en éste momento es:	**The lighting on your desk at this time is:**
Excesiva	Excessive
Alta	High
Adecuada	Adequate
Baja	Low
Muy Baja	Very Low

¿Se ve afectado en éstos momentos por reflejos o encandilamiento producto del sol?	**Are you currently affected by sun glare or reflections?**
Si	Yes
No	No

Si su respuesta es SI, los reflejos o encandilamientos se producen sobre:	**If you answered YES, the reflections or glare occur on:**
La Pizarra	The blackboard
El escritorio	The desk

La iluminación en la pizarra es:	**The lighting on the whiteboard is:**
Excesiva	Excessive
Alta	High
Adecuada	Adequate
Baja	Low
Muy Baja	Very Low

Annex 2

BUILDING CHARACTERIZATION CHECKLIST

1. Sala de clases

Fecha: _________ Hora: __________ Numero sala: _____

piso: ________

Profesor a cargo:____ Nivel del curso: _____

2. Edificio

Sala	**Ancho**	**Largo**	**alto**	
ventanas	**Ancho**	**Largo**	**alto**	**antepecho**
% ventanas	**Norte**	**Sur**	**Este**	**Oeste**

3. Clima

Temperatura exterior aproximada ____

Época del año: □ verano □otoño □ invierno □ primavera

Tipo de cielo:

□ Completamente cubierto

□ Medianamente cubierto
□ Un día cubierto y muy oscuro (usualmente días con lluvia y nubes obscuras)
□ Se puede ver parte del cielo descubierto entre las nubes desde la ventana de la sala de clases
□ Se puede ver parte del cielo descubierto entre las nubes SOLO desde el exterior de la sala de clases.
□ Es un día claro y descubierto, aunque no puedo ver sol directo desde el interior de la sala
□ Variable, con grandes nubes moviéndose y ocasionalmente sol.
□ Lluvia

4. Iluminación

De la siguiente lista elegir una opción de la columna a la derecha y luego una de la izquierda.

□ **Cortinas**	□ **Completamente cerrado**
□ **Persianas**	□ **¾ cerrado**
□ **Protección solar exterior**	□ **½ cerrado**
□ **Repisa solar**	□ **¼ cerrado**
□ **Otro tipo de protección**	□ **Completamente abierto**
□ **nada**	□ **nada**

Instalaciones de iluminación artificial

□ **Fluorescentes colgantes**	□ **Completamente apagado**

☐ Fluorescentes empotrados **☐ Otro** **☐ Nada**	**☐ ¾ apagado** **☐ ½ apagado** **☐ ¼ apagado** **☐ Completamente encendido** **☐ nada**
Actividad pedagógica	
☐ Clase centrada en el profesor **☐ Escritura/lectura en el puesto de trabajo** **☐ Uso de proyector**	**☐ trabajo manual / arte** **☐ Otro: ________________________** ________________________________

5. Calidad del aire

Porcentaje del vano con las ventanas abiertas (ahora)

☐ 10% ☐ 20% ☐ 30% ☐ 40% ☐ 50% ☐ 60%

Tipo de sistema de ventilación (si existiese):

_____________________________________ Esta en uso en este momento: ☐ si ☐ no

6. Equipos de medición

☐ temperatura aire– Humedad relativa
☐ temperatura radiante
☐ velocidad del aire
☐ CO2
☐ ruido ambiental DB
☐ Partículas MP10- MP25
☐ iluminancia plano trabajo
☐ iluminancia general
☐ fotografía HDR

7. Ocupación

Numero de alumnos en sala en este momento: _______

Clase anterior: _________________________________ Se desarrollo en la misma sala: ☐ si ☐ no

Alumnos en la sala de acuerdo a los codigos de encuesta. Dibuje ventana(s), pizarra, ubicación del profesor, puerta y norte en el esquema

8. Nivel de aislación de la ropa

Marque con una x el máximo nivel de ropa que es utilizado en ese momento por cada encuestado de acuerdo con su código de encuesta.

1. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

2. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

3. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

4. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

5. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

6. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

7. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

8. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

9. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

10. Código encuesta: _______ Clo calculado: __________

☐ Camisa o blusa ☐ camiseta o polera ☐ polerón o chaleco ☐ chaqueta
☐ blazer ☐ pantalones largos ☐ falda y medias gruesas ☐ falda

Annex 3

CONSENTIMIENTO INFORMADO ENCUESTAS

Estimado apoderado:

Quien suscribe, Muriel Díaz Cisternas, RUT: 15.325.841-4, candidata a doctor del doctorado en Arquitectura y Urbanismo (DAU) de la Universidad del Bío-Bío, reliza la investigación doctoral titulada: "Metodología para la evaluación de confort ambiental interior en aulas escolares mediante un indicador multicriterio", proyecto aprobado por el DAU, cuyo objetivo es estudiar la percepción del confort térmico, acústico, luminico y la calidad del aire de alumnos en aulas escolares.

El aula escolar y nivel en que su hijo/a se educa ha sido seleccionada como caso de estudio, junto con otros edificios escolares de la región del Bío-Bío. Asimismo, su hijo/a o pupilo ha sido seleccionado para participar de esta investigación a través de una encuesta de percepción de temperatura, ruido, iluminación y la calidad del aire que será aplicada en dos momentos del año y le tomará aproximadamente 30 minutos.

La información obtenida a través de este estudio será mantenida bajo estricta confidencialidad. El nombre de su hijo/a no será utilizado y la información será sólo almacenada por el investigador principal en dependencias institucionales, no existiendo copias de ésta. Esta información sólo será utilizada en esta investigación.

La encuesta será realizada en la sala de clases, la profesora repartirá hojas con la encuesta, mientras que la investigadora permanecerá en el pupitre de la profesora en caso de dudas. No habrá interacción ni cercanía entre la encuestadora y la(el) alumna(o) salvo verbal, en presencia de la profesora, y siempre desde el pupitre del profesor.

Usted tiene el derecho de retirar el consentimiento para su participación en cualquier momento.

El estudio no conlleva ningún riesgo para su salud ni recibe ningún beneficio. No recibirá compensación por participar. Los resultados grupales estarán disponibles en el Departamento de Diseño y Teoría de la Arquitectura de la Universidad del Bío-Bío si así desea solicitarlos. Si tiene alguna pregunta sobre esta investigación, se puede comunicar con Muriel Díaz al fono 41 3111303 o al correo electrónico madiazc@ubiobio.cl.

Este consentimiento se firmará en dos ejemplares, quedando uno en poder del participante.

Si desea contactarse con el Comité de Bioética y Bioseguridad de la Universidad del Bío-Bío, debe dirigirse al Sr. Pedro Labraña, Presidente del Comité al email: plabrana@ubiobio.cl, teléfono 41 311 1669.

Agradeciendo su participación, le saluda atentamente,

Muriel Díaz Cistermas

ACEPTACIÓN

Yo, ____, he leído el procedimiento descrito arriba. El investigador me ha explicado el estudio y ha contestado mis preguntas. Voluntariamente doy mi consentimiento para que mi hijo/a participe en el estudio de la Sra. Muriel Díaz Cisternas sobre ""Metodología para la evaluación de confort ambiental interior en aulas escolares mediante un indicador multicriterio". He recibido copia de este procedimiento.

________________________ Firma apoderado

________________________ Muriel Díaz Cisternas
Investigadora doctoral

Annex 4

Encuesta estudiantes

¡Hola! Tu curso ha sido seleccionado para un estudio sobre como se sienten ustedes dentro de la sala de clases. Te pedimos tu ayuda contestando estas preguntas. No hay respuestas buenas ni malas, sino que tienes que responder lo que piensas. ¡Muchas gracias!

Datos personales

Q 1. ¿Cuál es tu sexo?

□ Hombre □ Mujer

Q 2. ¿Qué edad tienes?

____

Q 3. ¿Usas lentes o lentes de contacto?

□ Si □ No

Q 4. **¿Como te sientes hoy?**

□ □ □ □ □

Sensación general

Q 5. **En este momento ¿Cómo PREFERIRÍAS el ambiente de la sala? Puedes elegir más de una opción.**

			Sin cambio			
Más frío	1	2	3	4	5	Más caluroso
Más ventilación	1	2	3	4	5	Menos ventilación
Más ruido	1	2	3	4	5	Menos ruido
Más luz natural	1	2	3	4	5	Menos luz natural

Q 6. **En este momento ¿Cómo SIENTES el ambiente de la sala?**

Muy malo	1	2	3	4	5	Muy bueno

Confort térmico

¿Cómo SIENTES la temperatura de la sala?	Muy desagradable	1	2	3	4	5	muy agradable
¿SIENTES frio o calor en la sala?	Muy frío	1	2	3	4	5	Muy caluroso
¿SIENTES que la temperatura al interior de la sala cambia durante el día?	Muy cambiante	1	2	3	4	5	Muy estable

Calidad del aire

Q 7. En este momento:

¿Cómo SIENTES el aire al interior de la sala?	Muy desagradable	1	2	3	4	5	muy agradable
¿SIENTES que el aire es muy húmedo o muy seco?	Muy húmedo/seco	1	2	3	4	5	Muy agradable
¿SIENTES que el aire es “pesado”?	Muy pesado	1	2	3	4	5	Muy agradable
¿SIENTES el olor de tus compañeros?	Muy fuerte	1	2	3	4	5	Sin olor
¿SIENTES olor a comida?	Muy fuerte	1	2	3	4	5	Sin olor

otro tipo de olor______________________

Confort acústico

Q 8. En este momento:

¿Cómo SIENTES el ambiente acústico de la sala?	Muy desagradable	1	2	3	4	5	muy agradable
¿SIENTES ruidos molestos?	Mucho ruido	1	2	3	4	5	Sin ruido
¿SIENTES ruido producido por tus compañeros?	Mucho ruido	1	2	3	4	5	Sin ruido

¿SIENTES ruido producido por otras salas?	Mucho ruido	1	2	3	4	5	Sin ruido
¿SIENTES ruido producido en la calle?	Mucho ruido	1	2	3	4	5	Sin ruido

Confort visual

Q 9. En este momento

¿Cómo SIENTES la iluminación de la sala?	Muy desagradable	1	2	3	4	5	muy agradable
¿SIENTES que la iluminación es?	Muy poca	1	2	3	4	5	suficiente
¿SIENTES reflejos en la pizarra?	ninguno	1	2	3	4	5	mucho
¿SIENTES que la Vista al exterior es agradable?	muy desagradable	1	2	3	4	5	muy agradable

Configuración espacial

Q 10. Cuando estas en esta sala, ¿Cómo SIENTES el espacio interior de la sala?

¿Cómo SIENTES el espacio interior de la sala?	Muy desagradable	1	2	3	4	5	muy agradable
¿SIENTES que los colores de las paredes son?	Muy aburridos	1	2	3	4	5	Muy entretenidos
¿SIENTES que la decoración es?	Muy aburrida	1	2	3	4	5	Muy entretenida
¿SIENTES que la Vista al exterior es agradable?	muy desagradable	1	2	3	4	5	muy agradable

Adaptación

Q 11. Cuando no te sientes cómodo en la sala de clases, ¿que tan probable es que hagas alguna de estas acciones?

Cuando hace frío o calor: Sacarme / ponerme ropa	Poco probable	1	2	3	4	5	muy probable

Cuando el aire esta pesado: Pedirle al profesor que abra la ventana	Poco probable	1	2	3	4	5	muy probable
Cuando hay mucho ruido: pedirle al profesor que hable mas fuerte	Poco probable	1	2	3	4	5	muy probable
Cuando hay mucha o poca luz: Pedirle al profesor que abra o cierre las cortinas	Poco probable	1	2	3	4	5	muy probable

Indulgencia

Q 12. Que aspectos son los más importantes para que te sientas confortable en la sala de clases

Sentir una temperatura agradable en invierno	Poco importante	1	2	3	4	5	muy importante
Sentir una temperatura agradable en verano	Poco importante	1	2	3	4	5	muy importante
Sentir el aire fresco y sin olores	Poco importante	1	2	3	4	5	muy importante
Sentir un ambiente silencioso	Poco importante	1	2	3	4	5	muy importante
Sentir una buena iluminación	Poco importante	1	2	3	4	5	muy importante

Tienes algún comentario sobre esta encuesta?

____

____

____

____

Annex 4 b: final version

Datos personales	
Nombre: / *Name*	**Curso:** / *Class*
¿Cuál es tu sexo? / *What is your gender?* ☐ Hombre/ *male* ☐ Mujer/ *female*	**¿Qué edad tienes?** / *How old are you?*
¿Usas lentes o lentes de contacto? / *do you use glasses or contact lenses?*	
☐ Si/yes	☐ no

¿Como te sientes hoy? / *How dou you feel today?*

☐ 	☐ 	☐ 	☐ 	☐ 

Sensación general / *General sensation*				
En este momento ¿Cómo <u>Preferirías</u> el ambiente de la sala? Puedes elegir más de una opción. / *Right now, how would you like the room to be?*				
☐ Más frío ☐ *Much colder*	☐ más fresco ☐ *Colder*	☐ Igual ☐ *The same*	☐ Más cálido ☐ *hotter*	☐ Más caluroso ☐ *Much hotter*
☐ Más ventilación ☐ *More ventilaiton*	☐ Un poco más ventilación ☐ *Little more ventilation*	☐ Igual ☐ *The same*	☐ Un poco menos ventilación ☐ *a Little les ventilation*	☐ Menos ventilación ☐ *Less ventilation*
☐ Más ruido ☐ More sound	☐ Un poco más ruido Little more sound	☐ Igual ☐ *The same*	☐ Un poco menos ruido ☐ *A Little less noise*	☐ Menos ruido ☐ *Less noise*
☐ Más luz natural ☐ *Much more natural light*	☐ Un poco más luz natural ☐ *A Little more natural light*	☐ Igual ☐ *The same*	☐ Un poco menos luz natural ☐ *A Little less natural light*	☐ Menos luz natural ☐ *Much less natural light*
En este momento ¿Cómo sientes el ambiente general de la sala? / Right now, How do you feel the general *environment of the room?*				
☐ Muy malo ☐ *Very bad*	☐ Malo ☐ *Bad*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Bueno ☐ *Good*	☐ Muy bueno ☐ *Very Good*

Temperatura / *Temperature*				
¿Cómo sientes la temperatura de la sala? / *How do you feel the temperature in the classroom right now?*				
☐ Muy desagradable ☐ *Very unpleasant*	☐ desagradable ☐ *unpleasant*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ agradable ☐ *pleasant*	☐ muy agradable ☐ *very pleasant*
¿<u>Sientes</u> frío o calor en la sala? *Do you feel hot or cold?*				
☐ Frío ☐ *cold*	☐ Fresco ☐ *Cool*	☐ Ni caliente ni frío ☐ *neutral*	☐ Cálido ☐ *Warm*	☐ Caluroso ☐ *hot*

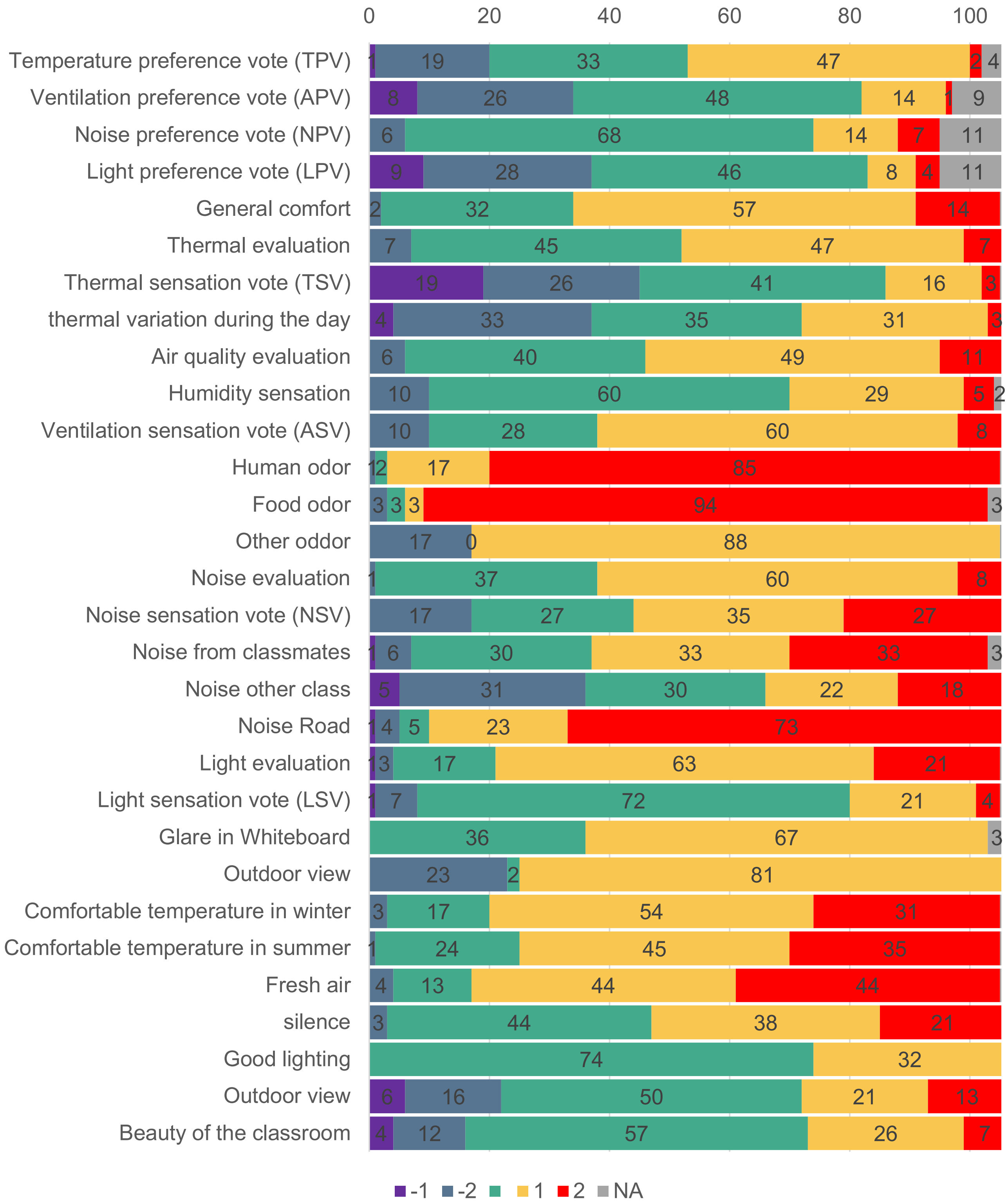
Aire / *Air*				
En este momento: ¿Cómo sientes el aire al interior de la sala? / *How do you feel the temperature in the classroom right now*				
☐ Muy desagradable ☐ *Very unpleasant*	☐ desagradable ☐ *unpleasant*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ agradable ☐ *pleasant*	☐ muy agradable ☐ *very pleasant*
En este momento ¿Como sientes la calidad del aire al interior de la sala? / *Right now: how do you feel the air quality inside the room?*				
☐ Muy pesado ☐ *Very heavy*	☐ Pesado ☐ *heavy*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ agradable ☐ *pleasant*	☐ muy agradable ☐ *Very pleasant*
En este momento ¿Sientes el olor de tus compañeros? / *Right now: do you feel the smell of your colleagues?*				
☐ Mucho olor ☐ *a lot of smell*	☐ Olor ☐ *some smell*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Poco olor ☐ *Little smell*	☐ Sin olor ☐ *no smell*
En este momento ¿Sientes olor a comida? / *Right now: Do you smell food?*				
☐ Mucho olor ☐ *a lot of smell*	☐ Olor ☐ *some smell*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Poco olor ☐ *Little smell*	☐ Sin olor ☐ *no smell*
En este momento ¿Sientes otro tipo de olor? / *Right now: Do you smell something else?*				
☐ Si / yes	☐ No	Cual / which?: ____________________________________		

Ruido / *Noise*				
En este momento: ¿Cómo sientes el ambiente acústico de la sala? / *Right now: How do you feel the acoustic environment of the classroom?*				
☐ Muy desagradable ☐ *Very unpleasant*	☐ desagradable ☐ *unpleasant*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ agradable ☐ *pleasant*	☐ muy agradable ☐ *very pleasant*
En este momento: ¿Sientes ruidos molestos? / *Right now: Do you feel disturbing noises?*				
☐ Muy ruidoso ☐ *Very noisy*	☐ Ruidoso ☐ Noisy	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Sin ruido ☐ Silent	☐ Nada de ruido ☐ No noise at all
En este momento: ¿Sientes ruido producido por tus compañeros? / *Right now: Do you hear noise from your classmates?*				
☐ Muy ruidoso ☐ *Very noisy*	☐ Ruidoso ☐ Noisy	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Sin ruido ☐ Silent	☐ Nada de ruido ☐ No noise at all
En este momento: ¿Sientes ruido producido en otra sala? / *Right now: Do you hear noise coming from another room?*				
☐ Muy ruidoso ☐ *Very noisy*	☐ Ruidoso ☐ Noisy	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Sin ruido ☐ Silent	☐ Nada de ruido ☐ No noise at all
En este momento: ¿Sientes ruido producido en la calle? / *Right now: Do you hear noise coming from the Street?*				
☐ Muy ruidoso ☐ *Very noisy*	☐ Ruidoso ☐ Noisy	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ Sin ruido ☐ Silent	☐ Nada de ruido ☐ No noise at all

Luz / *Light*				
En este momento: ¿Como <u>sientes</u> la iluminación en la sala? / *Right now: How do you feel the lighting in the room?*				
☐ Muy desagradable ☐ *Very unpleasant*	☐ desagradable ☐ *unpleasant*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ agradable ☐ *pleasant*	☐ muy agradable ☐ *very pleasant*
En este momento: ¿<u>Sientes</u> que la iluminación es ...? / *Right now: do you feel that light is...?*				
☐ Muy poca ☐ *too little*	☐ poca ☐ *little*	☐ Ni bien ni mal ☐ *Neither good nor bad*	☐ mucha ☐ *a lot*	☐ demasiada ☐ *too much*
En este momento: ¿Ves reflejos en la pizarra? / *Right now: do you see reflections on the whiteboard?*				
☐ Si / *yes*	☐ No			
En este momento: ¿<u>Sientes</u> que la vista al exterior es agradable? / *Right now: do you feel that the view from the window is nice?*				
☐ Si / *yes*	☐ No	☐ No veo por que la cortina esta cerrada ☐ *I can't see why the curtain is closed*		

General / *General*				
Que aspectos son los más importantes para que te sientas confortable en la sala de clases / *What are the most significant aspects for you to feel comfortable in the classroom?*				
Sentir una temperatura agradable en invierno / *Feeling a comfortable temperature in winter*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Sentir una temperatura agradable en verano / *Feeling a comfortable temperature in summer*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Sentir el aire fresco y sin olores / *Feeling fresh air and no odour*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Sentir un ambiente silencioso / *Feeling a quiet environment*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Que exista una buena iluminación / *Good lighting*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Vista al exterior / *View to the outside*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*
Que la sala sea bonita / *That the room looks nice*				
☐ Nada importante ☐ *Not important*	☐ poco importante ☐ *A little important*	☐ Me da lo mismo ☐ *I don't care*	☐ Importante ☐ *Important*	☐ Muy importante ☐ *Very important*

Annex 5



0
20
40
60
80
100
Temperature preference vote (TPV)
Ventilation preference vote (APV)
Noise preference vote (NPV)
Light preference vote (LPV)
General comfort
Thermal evaluation
Thermal sensation vote (TSV)
thermal variation during the day
Air quality evaluation
Humidity sensation
Ventilation sensation vote (ASV)
Human odor
Food odor
Other oddor
Noise evaluation
Noise sensation vote (NSV)
Noise from classmates
Noise other class
Noise Road
Light evaluation
Light sensation vote (LSV)
Glare in Whiteboard
Outdoor view
Comfortable temperature in winter
Comfortable temperature in summer
Fresh air
silence
Good lighting
Outdoor view
Beauty of the classroom
-1
-2
1
2
NA