Thermal Comfort and Indoor Air Quality in Low Socioeconomic Status Classrooms

by

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Dissertation Abstract

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Indoor air quality and thermal comfort influence student performance and wellbeing in schools. Most studies in this area have concentrated on measuring classroom environmental conditions and comparing them with student's perceptions of comfort, specific academic tasks, or measures associated with health, like absenteeism. This approach, though valid, ignores the influences that modify and dictate classroom indoor conditions. For example, most adaptive opportunities (such as window operations or thermostat) are in the immediate control of the teacher, not the students. Additionally, facility maintenance and operations managers have specific policies and mandates that regulate and control the indoor environmental conditions of classrooms; many of these related to aging school facilities and limited funding. This is most pressing for schools located in disadvantaged communities, which often do not have sufficient funds to maintain or modernize their schools and may suffer more from chronic exposures to unhealthy environmental conditions. The objective of this dissertation is to characterize the environmental performance of low-socioeconomic classrooms in different contexts and investigate how teachers, facility maintenance and the classroom physical environment influence their indoor environmental conditions. The dissertation presents five chapters that investigate different aspects of indoor air quality and thermal comfort. The first chapter describes the mixed-method case study approach used in the subsequent chapters to study thermal comfort and indoor air quality in schools. The methodology aims to construct a holistic understanding of the building, occupant, and maintenance factors that influence indoor environmental quality in educational settings.

The following chapters present three case studies that took place in schools in different locations in the Americas: Eugene, Oregon, Southern California, and Gran Concepción in Chile. The Oregon case study assessed the efficiency of ventilation strategies and protocols in one classroom during the COVID-19 pandemic for CO_2 and particulate matter ($PM_{2.5}$ and PM_{10}) concentrations. The study found that since the outdoor air quality and temperatures were relatively ideal during the study period, occupancy levels, and teachers' adaptive behaviors and activities were the major influences on indoor air quality. While the results are not generalizable, the case study showed that, on average, during mild weather seasons like the

spring, natural ventilation could provide adequate ventilation rates for the classroom during normal use, and near optimal ventilation during emergency use, if all doors and windows remained open.

The following case study investigated particulate matter concentrations ($PM_{2.5}$ and PM_{10}) in three schools in the Gran Concepción region in Chile, along with a survey of self-reported health symptoms from teachers. This area is characterized by high levels of energy poverty, so wood stoves are widely used to heat residences. In the three schools, indoor and outdoor $PM_{2.5}$ and PM_{10} surpassed the World health Organization's (WHO) air quality guidelines (AQG), and in some cases reached environmental emergency levels according to Chilean local regulations. Also, outdoor air pollution stemming from wood stove burning smoke and traffic didn't appear to be an important health concern for teachers. The symptoms teachers reported more frequently matched those related to teaching in previous literature. The case study portrayed the urgency of improving IAQ in the region and showed the disconnect between air pollution concentrations and the chronic exposure concerns of teachers in a context of energy poverty.

The final case study investigated the ways in which classrooms' physical environment, teachers, and maintenance managers, influenced thermal conditions and IAQ in low socioeconomic status Southern California schools using a mixed-methods approach. The qualitative portion of the case study found that the construction of indoor environmental conditions in classrooms depended on 1) the effective communication between teachers and maintenance managers, 2) the adaptations to the classroom environment resulting from comfort, teaching and learning influences, and 3) managers' ability to plan and execute maintenance, and respond to emergencies. These findings were complemented with the quantitative portion of the case study, where permanent classrooms of all ages and conditions outperformed portable classrooms regarding thermal comfort and ventilation. In addition, the thermal performance of classrooms directly reflected each school district's temperature policies, and the results suggested that including controlled adaptive opportunities for teachers could be beneficial for energy efficiency and occupant comfort. The case study showed that teacher awareness, education, and training on indoor environmental quality are vital for the optimum use of building systems and the creation of ideal environmental conditions in classrooms.

This dissertation includes previously published and unpublished co-authored material.

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1. Introduction

The importance of thermal conditions and indoor air quality (IAQ) in classrooms is well-established in scholarly literature, as these factors have been associated with student performance, health, and comfort, thereby influencing teaching and learning. Children are more vulnerable than adults as they breathe more air per unit weight and are more sensitive to cold, heat, and moisture (Sadrizadeh et al., 2022). The effects of heat on performance have been associated with distraction, discomfort, and thermal discomfort physiological effects (Wargocki & Wyon, 2017), with studies observing that slightly reducing temperatures in classrooms can improve student's schoolwork in numerical, language, concentration, and logical thinking tasks, mainly in terms of speed (Haverinen-Shaughnessy & Shaughnessy, 2015; Riham Jaber et al., 2017; Wargocki & Wyon, 2007a, 2013). In addition, studies looking into large data bases have found that hot days decrease test scores, and suggest that cumulative heat exposure can reduce the rate of learning (J. Park et al., 2016; R. J. Park et al., 2021).

Studies researching ventilation and indoor air quality (IAQ) have shown similar results. Various studies have found associations between increased student performance and higher ventilation rates or lower CO_2 concentrations (Bakó-Biró et al., 2012; Haverinen-Shaughnessy et al., 2015; Haverinen-Shaughnessy & Shaughnessy, 2015; Toftum et al., 2015; Wargocki & Wyon, 2007a, 2007b, 2013). These studies have used a multiplicity of approaches to measure performance in relation to ventilation, including specific tests (e.g. attention and vigilance, etc.), academic tasks (Wargocki & Wyon, 2017), and major test score databases (Toyinbo et al., 2016), and compared them with on-site measurements. Like with comfort, the mechanisms through which poor indoor air quality affects cognitive performance are thought to be attention or distraction, motivation, arousal, neurobehavioral symptoms, and acute health symptoms, sleep quality, and absenteeism (Wargocki & Wyon, 2017). Despite this evidence, classrooms do not usually meet the minimum ventilation requirements specified in the standards (Daisey et al., 2003; Fisk, 2017; Shendell et al., 2004; Wargocki & Wyon, 2013) no matter their ventilation type (naturally ventilated, hybrid or mechanically ventilated) (Fisk, 2017). This is an issue for schools, as pollutants like particulate matter or VOCs can accumulate easily in poorly ventilated spaces, and may cause acute or chronic health symptoms, impacting the wellbeing and academic performance of students (Mendell & Heath, 2005).

This evidence shows how most thermal comfort and ventilation studies in schools have concentrated on children's perceptions, performance and health. However, teachers are usually in control of the environment of classrooms, (e.g. opening/closing of windows, doors, fan and thermostatic controls), especially in lower grades where students have all their subjects in one room. In such cases, students become passive receivers of the environment, and classroom conditions tend to resemble the preferences of the teacher. Children's involvement in adjusting the classroom environment is then uncertain because they often need the permission of the teacher to modify their environment, or are constrained by the school dress code and behavioral rules (de Dear et al., 2020). In addition, children might not be sufficiently environmentally aware to modify their environment at a young age (Bernardi, 2006). Since students are not dictating the environmental conditions of classrooms, it is necessary to take a step back and investigate those who are.

In addition to this disconnect, inadequate indoor quality in classrooms can result from poor management, operation, maintenance, and cleaning (Sadrizadeh et al., 2022). In the US for example, schools are aging, and many are in need of retrofit. As of 2020, it was estimated that 54% of public-school districts needed to update or replace multiple building systems, and among them, a 41% needed to update or replace their heating, ventilation and air conditioning systems (HVAC) in at least half their schools (U.S. Government Accountability Office, 2020). Despite representing the second largest public infrastructure spending in the country, there is no comprehensive national data source on K-12 public school infrastructure (American Society of Civil Engineers (ASCE), 2021), and as of 2021, a report estimated an underinvestment in school buildings and grounds of 85 billion US dollars each year and a subsequent gap of 27.6 billion USD for Maintenance and Operations (M&O) (International Well Institute et al., 2021). With aging schools and systems, and the existing underinvestment in school infrastructure, the role of facility maintenance and operations managers, also becomes key to understanding the nuances behind indoor air quality and thermal conditions in classrooms.

These issues are even more exacerbated in vulnerable and low-income communities. For instance, US school districts have to cover the majority of their capital facility costs, so "poor and low-wealth districts are frequently unable to adequately maintain their buildings and grounds, much less modernize their schools." (Filardo et al., 2019). And this situation isn't new. A report form 2006 found that even with unprecedented spending and growth for school construction in the US in the previous decade, the billions of dollars spent on school facilities were not equally available for affluent and low-income communities,

and for minority and white students (Filardo et al., 2006). Even more, funds for school facilities are often spread unequally across and between states, because of politics and the ability to apply to available funds (Baker & Bernstein, 2012).

It has been shown that schools with the greatest need for repair are attended by disadvantaged or minority students, and associated with high absenteeism (Eitland, 2020). The most vulnerable communities tend to be more prone to suffer from poor air quality or extreme weather conditions. For example, international studies have shown disparities in the thermal preferences of children in low-income and higher-income classrooms (Trebilcock et al., 2017). And even more pressing, a recent study showed that heat exposure events influence on learning vary significantly between socioeconomic groups, both in the US and internationally. In the US, the inhibition of learning during high temperatures was almost 3 times larger for lower income students. With air conditioning use widespread in the US, it is possible that in tropical economies, these extreme weather events have even larger consequences (R. J. Park et al., 2021).

It is then necessary to give a new look at what influences indoor air quality and thermal comfort in schools, from the design of classrooms and the systems that create indoor environmental conditions, to the actions and adaptations of users and the stakeholders that maintain and operate school facilities. Classrooms' design and systems provide opportunities for adaptation and set up the baseline for the creation of indoor environmental conditions. Teachers occupy and modify the classroom space directly, while maintenance managers and staff modify and dictate what occurs to that space more indirectly. To improve the indoor environments of classrooms, it is important to first understand the nuances, stakeholders and mechanisms at play to generate them. Only in this way we will be able to create healthier school environments for students.

With these ideas in mind, the objective of this dissertation is to characterize the environmental performance of low-socioeconomic classrooms in different contexts and understand the stakeholders, physical spaces, and interactions that play a crucial role in generating those conditions. The dissertation presents five chapters that investigate different aspects of indoor air quality and thermal comfort in schools. These include one methodology chapter, along with three studies that took place in schools in three locations in the Americas: Eugene, Oregon, Southern California, and Gran Concepción in Chile, portraying multiple how this problem takes different faces depending on the location. The schools in the

last 2 studies are in low-socioeconomic status areas, and the findings portray the issues that these contexts and school districts face.

To start, Chapter 2 outlines a methodological approach for conducting case study research for indoor environmental quality by investigating the relationships between facility management, teacher environmental perceptions, and the physical environment of classrooms. Most studies in this area use quantitative methods such as physical measurements and surveys to assess the existing conditions of classrooms and contrast them with user, typically student perceptions. While valuable, this approach overlooks critical elements that shape or alter these conditions, such as school facilities' maintenance practices and operations (routine systems maintenance, filter changes, etc.), custodial practices (custodial cleaning, mopping, sweeping, etc.), teacher interactions with building and systems (thermostat use, opening windows and doors, etc.), and the communication between school occupants and facility management and maintenance.

The objective of the methodology is to understand the mechanisms that create adequate thermal and IAQ conditions in learning spaces. The approach aims to gain a broad view of aspects that often remain hidden in indoor environmental quality studies by highlighting the use of targeted semi-structured interviews with key stakeholders as a complement to traditional quantitative methods. Drawing insights from three primary sources —teachers, facility maintenance officers, and the physical conditions of classrooms— the methodology aims to construct a holistic understanding of the building, occupant, and maintenance factors that influence indoor environmental quality in educational settings.

Following the general outline of the methodology, the following chapters of the dissertation include case studies that use part, or all the information gathered with the methodology, and introduce different aspects of IAQ and thermal comfort in classrooms that were salient in each case study.

Chapter 3 presents a pilot study developed in a naturally ventilated classroom in Eugene, Oregon, at the end of the COVID-19 pandemic. During this time, schools were pushed to change how they operated and ventilated their classrooms, so school districts and facility managers created protocols to improve their facilities to provide adequate indoor air quality (IAQ) for the health and safety of their students. Therefore, the objective of the study was to assess ventilation in the classroom considering the pandemic

recommendations. To develop the case study, measurements of carbon dioxide, indoor and outdoor particulate matter (PM), temperature, and relative humidity were taken along with recordings of occupancy and user behaviors related to window and door operation. During this period, the school had protocols for ventilation put in place, so measurements were useful to assess the relevance and efficiency of the protocols.

In this case study, particulate matter 2.5 μg/ m3 (respirable) and 10 μg/ m3 (inhalable) concentrations reached moderate levels during cleaning periods when the students were not present. The average CO_2 concentration during periods of high occupancy was 608 ppm, which placed ventilation between 4 and 5 air changes per hour (ACH), while periods of high occupancy with the front door open reached an average of 565 ppm, closer to the target 6 ACH recommended during the pandemic. Since outdoor air quality was relatively ideal during the study period, occupancy levels, adaptive behaviors and activities were the major influences on indoor air quality. Informal conversations with teachers and principals allowed for an understanding of the general attitudes about classroom conditions, protocols, and policies by facility management and leadership.

This case study was intended as a pilot to develop and verify methods for a more extensive study into schools with different ventilation systems and other climates. It was limited by a small sample size and measuring period of a mild weather season, which did not allow for generalizable conclusions. Given these limitations, the two case studies presented in Chapters 4 through 6 represent further attempts to surpass these limitations and reach more robust results.

The case study presented in Chapter 4 uses a similar approach and concentrates on the quantitative portion of the methodology, to make connections between air quality and teacher health in the context of energy poverty in Gran Concepción, Chile. The chapter stems from the same theoretical background as the one presented in Chapter 3, but considers the nuances of the Chilean context, which becomes the driver of the research. The case study originates from the idea that most of the existing evidence of associations between particulate matter, respiratory diseases, and increases in mortality from all causes comes from developed countries, whereas studies from middle to low-income countries are limited (Chen & Hoek, 2020). In Chile, high levels of energy poverty have been identified in the central-southern towns of the country, where the primary means for household heating are wood stoves (CDT, 2015; Reyes et al.,

2019). These generate periods of high air pollution during the winter and may exacerbate preexisting health conditions that affect vulnerable populations.

Air pollution from energy poverty goes beyond residential buildings and impacts public spaces and buildings near residential areas, like schools. Chapter 4 presents an analysis of indoor and outdoor air quality along with a survey of self-reported health symptoms of teachers in public schools in Chile, located in areas of energy poverty during the winter of 2023. Indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations were monitored for a school week in three schools in the Gran Concepción metropolitan area, and particulate matter concentrations were compared with the WHO Air Quality Guidelines (AQG) and local air quality regulations. Indoor and outdoor $PM_{2.5}$ surpassed the AQG recommended levels of air pollution, with the highest concentrations occurring in the evenings and nights. In addition, the survey showed that almost a third of teachers ranked the outdoor air quality in the previous week as "bad," but only 13% saw outdoor air pollution as an important health concern. The symptoms teachers reported as being more frequent included those related to teaching, such as hoarse-dry throat, and respiratory health, like irritated, stuffy, or runny nose. This case study portrays the reality and urgency of Chilean classrooms regarding indoor and outdoor air quality during the winter months and discusses the health implications of teaching and learning in the context of energy poverty.

While Chapters 3 and 4 have a narrower scope and concentrate on quantitative measurements, Chapters 5 and 6 are more holistic, and fully develop the mixed-method approach in the case study of Southern California Schools. Chapter 5 concentrates on the qualitative portion of the analysis, and investigates how the relationships between maintenance managers, teachers, and the classroom's physical environment co-construct the indoor air quality and thermal conditions in Southern California classrooms. The Chapter uses a grounded theory approach to analyze 14 semi-structured interviews conducted with teachers and Maintenance Managers in 6 schools across 3 low-socioeconomic status school districts in Southern California.

This analysis revealed that the interactions between teachers, managers and the physical environment of the classroom shape the indoor environmental quality and thermal conditions of learning environments, and are constructed through 1) the effective communication and response between teachers and maintenance managers, 2) the adaptations to the classroom environment that result from environmental

influences on comfort, teaching and learning, and 3) the planning and execution of maintenance, along with the ability to respond to emergency situations. Adequate indoor air quality and thermal conditions in classrooms result from complex relationships, which depend on aspects that go beyond technical explanations and highlight the impact of human and non-human actors. Through the narrative created in the chapter, critical aspects of design, management, and use practices of environmental controls in classrooms gain relevance for indoor environmental quality discourses.

Finally, Chapter 6 develops the quantitative portion of the Southern California case study and revisits a portion of the findings introduced in Chapter 5, to triangulate the data and provide a more robust analysis of the case study. It presents a post-occupancy evaluation of 12 low-socioeconomic status classrooms, sampled in 6 schools in 3 school districts in Southern California after the COVID-19 pandemic. Through a mixed-method approach, the case study aims to understand how teachers' adaptations, management decisions and the classroom physical environment influence the thermal comfort, ventilation and IAQ performance of classrooms.

In this chapter, indoor and outdoor physical measurements of environmental parameters are paired up with semi-structured interviews with the teachers of the measured classrooms and maintenance managers in the districts. In this way, it is possible to quantitatively assess the conditions of classrooms and simultaneously create a narrative that qualitatively explains and complements the quantitative findings. Permanent classrooms of all conditions -new, recent retrofit and old retrofit- outperformed old portable classrooms regarding thermal performance and ventilation. In addition, teachers' actions and facility maintenance were proven to be essential in shaping the environmental conditions of classrooms. The results showed that communication between managers and teachers is strategic to maintaining adequate environmental conditions in classrooms. Finally, the study revealed the importance of building maintenance capacity in school districts, as well as teacher awareness and education on classroom operation for adequate indoor environmental quality as keys for the creation of optimal learning environments.

All the chapters in this document were prepared for publication. Chapters 3 and 4 were written in co-authorship and are published in the Architectural Research Centers Consortium (ARCC) conference

proceedings from 2023 and 2024 respectively. Chapter 3 was written with Professor Alison Kwok, while Chapter 4 was written with Professors Isabel Rivera, Andrea Martínez and Alison Kwok.

The methods and results presented in this dissertation show the current state of low-socioeconomic schools, how they are performing regarding indoor air quality and thermal comfort. But more importantly, they touch on the mechanisms and stakeholders that play a role in creating optimal environments for children in classrooms. It is my hope that the results from these studies will serve the schools and districts that collaborated with the study, and might be extrapolated to other contexts, so that schools can tackle the multiple challenges they face every day.

2. Methodological Approach for Investigating Thermal Comfort and Indoor Air Quality in School Facilities through Case Study Research

The methodology described in this chapter was conceptualized, developed, written and reviewed by Maria C. Coronado. The manuscript was prepared for future publication.

2.1. Introduction

Adequate thermal conditions and indoor air quality (IAQ) in educational buildings are important influences for teaching and learning. The main hypothesis behind this is that poor indoor environmental quality caused by building characteristics and faulty HVAC systems, produces adverse health effects, discomfort and distraction, which reduces student attendance and academic performance (Mendell & Heath, 2005). Therefore, most IAQ and thermal comfort (TC) studies in schools use quantitative methods and concentrate on specific results, often studying associations between occupants' perceptions, health assessments, and perceptions with classrooms' environmental conditions.

In schools, both IAQ and TC represent contending issues. Children breathe more air per unit of weight than adults and are more vulnerable to changes in temperature (Sadrizadeh et al., 2022), so classroom environments have a large effect on their health. However, research has found compelling evidence that schools of all ventilation types are often under ventilated in comparison with the standards (Fisk, 2017). Researchers have often used CO_2 concentrations as a proxy for ventilation to help understand the concentrations of other pollutants during human occupancy, finding that classrooms often exceed concentrations of 1000 ppm of CO_2 for long periods of time (Wargocki & Wyon, 2013). This can affect students, as IAQ has been associated with multiple mechanisms that affect mental performance including distraction and attention, motivation, arousal, neurobehavioral and acute health symptoms, sleep quality, and absenteeism (Wargocki & Wyon, 2017).

In addition, inadequate ventilation can result in ineffective dilution or removal of harmful pollutants present in the air. In schools, studies have found a wide range of pollutants including volatile organic compounds (VOC), NO_2, CO, ozone (O_3), particulate matter, as well as exposures to fungi and bacteria,

which have been related to respiratory symptoms (Sadrizadeh et al., 2022). Among these pollutants, particulate matter PM_{10} and $PM_{2.5}$ are a common concern, as they have well known health effects. In particular $PM_{2.5}$ has been associated with cardiovascular, respiratory, and long-term lung cancer mortality (Chen & Hoek, 2020). The presence of $PM_{2.5}$ in classrooms is context-dependent, varying based on factors such as season and location (Habil & Taneja, 2011). This methodology only considers CO2 concentrations to assess ventilation and PM_{10} and $PM_{2.5,}$ as these are two of the most common study variables.

Thermal comfort and indoor air quality are closely related, as adaptive actions to improve one often affect the other, especially in naturally ventilated buildings. Research has shown how increased ventilation rates and maintaining temperatures within a recommended threshold can have beneficial effects for some aspects of students' performance, like speed response (Wargocki & Wyon, 2007b, 2013). In addition, multiple studies have found that children prefer lower temperatures than adults, in conditions often fall outside the static standard comfort zone (de Dear et al., 2020).

In these kinds of studies, the context where indoor environmental conditions occur is often overlooked, as it carries multiple confounding variables that are difficult to assess in quantitative studies. Nonetheless, its importance has been recognized, as when contextual factors are accounted for in quantitative studies, they have significantly influenced important measures like thermal sensations (F. Zhang & de Dear, 2019), or ventilation rates (Korsavi et al., 2020). To gain a better understanding of the multiple influences that play a role in the indoor environmental quality of classrooms, it is necessary then to include other variables, and assess them qualitatively, as they may help to understand how to create adequate indoor environmental quality in schools.

This document bridges this research gap by proposing a mixed-method case study research approach. This methodology is designed to uncover diverse aspects that influence indoor environmental quality in schools that may remain obscured when exclusively relying on quantitative methods. Case study research offers a holistic examination of the problem, delving more deeply into multiple facets of a phenomenon and considering contextual conditions. This approach is advantageous as it offers insights into the reasons or mechanisms behind a phenomenon, providing complementary information to quantitative research (Yin, 2018).

2.2. Methodology definition

This methodology stems from the proposition that comfortable and healthy indoor environmental quality (IEQ) for thermal conditions and indoor air in schools, is influenced by the behaviors of school occupants, the facility management and operation practices, the building, and its specific context. Therefore, the methodology addresses the following question:

How can the relationships between facility maintenance, occupants and the physical environment provide adequate IAQ and thermal conditions? (Figure 2-1).

To explore and describe these relationships, the methodology draws information from three sources: the classroom environment (building and context), facility managers and maintenance staff (maintenance and operations practices), and schoolteachers (school occupants). The selection of these sources of information has to do with their relevance and availability across multiple case studies. Quantitative studies commonly address the building and its context, providing details about ventilation systems, orientation, general design, and other factors that serve as references to explain specific characteristics of a case study or to facilitate comparisons between cases. Additionally, these studies usually include characteristics such as the season, location of the building (rural, urban, suburban), and various climate parameters (temperature, humidity, wind speed, etc.) that may influence the results and analysis of the study. Moreover, physical measurements of specific environmental parameters, gases, or pollutants relevant to the study are often included. The methodology maintains a quantitative approach by systematically recording typical environmental parameters and common air pollutants related to the study of TC and IAQ.

Thermal Comfort and Indoor Air Quality studies in schools typically focus on the student population, as the primary driver of these studies is to provide healthy and comfortable environments for children. Yet it is essential to recognize that the assessment of indoor environmental conditions in a classroom is not solely for students, nor are they typically in control. Research suggests that teachers' preferences often play a significant role in shaping the indoor environmental conditions of classrooms, sometimes even more so than students' preferences (de Dear et al., 2020). This phenomenon arises from constraints on students' control of the classroom environment, such as needing permission from the teacher or adherence

to school rules. Younger students are often passive receivers of the environment, and lack environmental awareness to provide meaningful survey or interview responses (Bernardi, 2006). In addition, studies have found that in naturally ventilated classrooms about 80% of window operation is carried out by teachers who have different comfort preferences to children (Korsavi & Montazami, 2020).

To address these challenges, this methodology places teachers as the primary study population. Given their continuous exposure to the classroom and daily interaction with students, teachers can offer valuable insights into the indoor environmental quality of the classroom. Additionally, involving teachers provides an understanding of how they control the classroom environment and offers insights into contextual factors such as school protocols, practices, and specific adaptations often overlooked in quantitative studies. This methodology employs semi-structured interviews with selected teachers and a general survey distributed to all teachers in the school. This dual approach aims to provide both a broad overview of teachers' perceptions of the school environment and a more in-depth understanding of specific classrooms.

While facility maintenance and operation of school buildings are often overlooked in TC and IAQ studies, they play a fundamental role in maintaining adequate indoor air and thermal conditions. After the increased ventilation and filtration needs generated during the COVID-19 pandemic, and with about 36000 school facilities in the US only, in need of upgrading or fully changing their HVAC systems (U.S. Government Accountability Office, 2020), the work of facility managers is without doubt, a key factor to maintaining optimal indoor environmental conditions in classrooms. Managers regulate indoor environmental conditions in schools and oversee maintaining the systems that provide them. Typically, studies addressing school maintenance rely on expert checklists or existing databases of facilities assessments (Durán-Narucki, 2008; Maxwell, 2016). However, not all schools or school districts have such detailed documentation or are willing to share it. To address this gap, the methodology includes interviews with facility managers and maintenance staff. This approach aims to gain in-depth knowledge of the specific maintenance and operations practices carried out in each case study. By directly engaging with these key stakeholders, it is possible to gather valuable insights into the strategies and practices employed to ensure a conducive indoor environment in educational buildings, contributing to a more comprehensive understanding of factors influencing indoor environmental quality in school settings.

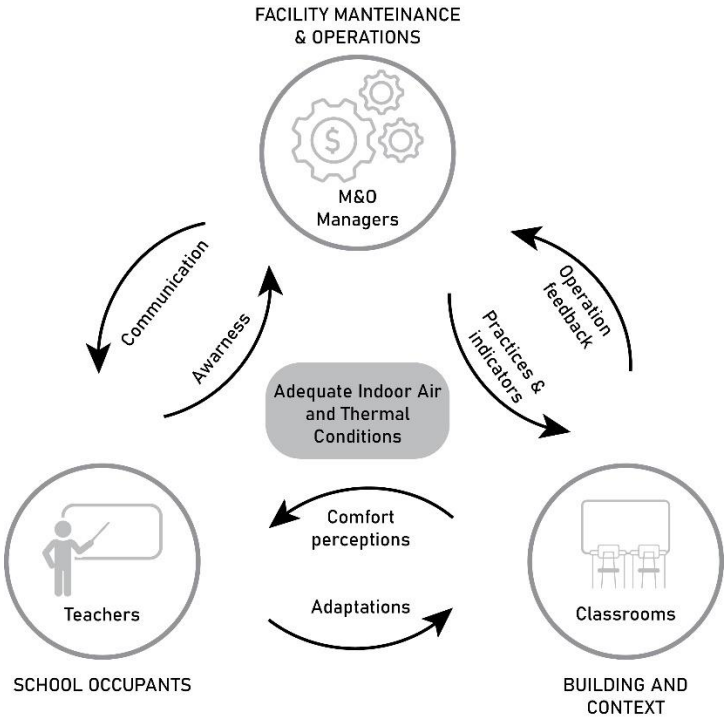


Figure 2-1 Relationships inquired in the methodology

2.3. Methodology description

2.3.1. Planning and documentation

The first step was to consider case studies that followed a clear set of criteria. Common characteristics were employed to group a set of schools or classrooms, while differing characteristics provided a basis for contrasting between cases. For example, climate, location, and ventilation systems were common characteristics of a group of schools, while age of the facility or type of classroom served as a differentiating factor for comparison. These criteria were selected during the research design phase in each location or school district to ensure that the chosen case studies aligned with the research objectives.

In the preparation phase, it was necessary to obtain all necessary permissions from Institutional Review Boards or other research oversight entities before starting the research activities. Once the required approvals were secured, coordination with school and/or school district officials became paramount prior to selecting the specific schools and classrooms for the study. At least one preliminary visit to the schools was conducted to do a reconnaissance of the school facility, select the classrooms, and introduce the project to the teachers and facility maintenance personnel. This initial visit allowed for the coordination and planning of surveys, interviews, and the setup for the measuring equipment station.

During this phase, basic building and context information that may influence the thermal and IAQ conditions of classrooms was gathered (Table 2-1). Contextual information, such as climate and seasonal patterns allowed for understanding the heating and cooling needs of each site. Additionally, the location and proximity of neighboring buildings or roads provided information on possible impacts on indoor environmental quality.

Table 2-1 Building and context information gathered

	Type of information	Variables
Context	Climate information	Temperature, humidity, windspeed, solar radiation, seasonal heating and cooling needs
	Location	Rural, urban, suburban, nearby roads, industries, other
Building	General information	Regulations, building age, construction materials,
	Building plans	Orientation, classroom area and volume, window number and location
	Mechanical systems	Ventilation type, age, location
	Operation	Educational level, administration model, schedule

Collecting information about the building and the classrooms was equally important during this phase. General building information helped frame the case study. Plans and sections were useful to select the classrooms and provide basic information for the physical measurements and calculations. Information on mechanical systems was important for determining the analysis approach and informing the results. Lastly, understanding the school's operation regarding school hours, and classroom occupancy schedules

was key to characterizing the case study and defining when to conduct physical measurements. This comprehensive information-gathering process ensured a well-informed and contextually rich foundation for the research.

2.3.2.Data collection

2.3.2.1. Physical measurements

This methodology used the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard measuring protocols of environmental parameters to assess thermal comfort and ventilation. Protocols and parameters to assess thermal comfort are included in the ASHRAE Standard 55-2023 Thermal Environmental Conditions for Human Occupancy (ASHRAE, 2023b). Similarly, ASHRAE Standard 55-2023 includes multiple methods that employ indoor CO_2 concentration to calculate ventilation rates (VRs) per person when combined with additional information such as space type, occupant density, and occupant characteristics (Allen et al., 2020; Batterman, 2017; Luther et al., 2018). The ASHRAE Standard 62.1-2022 for Adequate Indoor Air Quality in Buildings includes VR recommendations for different types of buildings (ASHRAE, 2022a). In this methodology, the proposed parameters for the assessment of VRs and TC were based on the guidance given in these documents and are referenced in

Table 2-2.

In addition to thermal comfort and ventilation rates, the methodology focused on the study of particulate matter binned at 2.5 microns ($PM_{2.5}$) for IAQ in classrooms, as it constitutes a significant concern due to its association with multiple health issues, including cardiovascular, respiratory, and long-term lung cancer mortality (Chen & Hoek, 2020). International agencies and governments including the World Health Organization (WHO), and the US National Ambient Air Quality Standards (NAAQS) have created diverse recommendations for $PM_{2.5}$ exposure thresholds for different time spans of exposure to $PM_{2.5}$ (EPA, n.d.; WHO, 2021).

Table 2-2 Parameters to measure, calculate or record during the physical measurements.

Source	Parameter	Use	Method
Indoor Environment	CO_2	VRs	Directly measured using interior dataloggers
	$PM_{2.5}$	IAQ	
	Air Temperature	TC	
	Relative humidity		
	Air speed		
	Globe temperature		
	Operative temperature		Calculated (ASHRAE, 2021, 2023b)
	Mean Radiant Temperature		
Outdoor environment	CO_2	VRs	Directly measured using exterior dataloggers
	$PM_{2.5}$	IAQ	
	Air Temperature	TC	
	Relative humidity		
Occupants	Activity levels	TC, VRs	Observation log
	Clothing insulation	TC	
	Age	VRs	Interviews and secondary information from (Batterman, 2017)
	Body mass		
	Adaptations	TC	Window/door opening sensors
Building	Area	VRs	Directly measured with measuring tape
	Volume	VRs	
	Occupancy		Motion sensors, observation log
	Ventilation type	TC	Observation log
	Window operation, % and location		

The timeframe for conducting physical measurements was one week, encompassing both occupied and unoccupied periods to capture the typical operation of classrooms. Monitoring equipment was positioned at 1.1 m height (43 in) above the finished floor following the current ASHRAE 55 standard, which is also inside the recommended breathing zone of ASHRAE standard 62.1. Additionally, equipment was placed as far away as possible from windows and doors to reduce drafts or direct solar radiation. Lastly, the

monitoring equipment was positioned near the front or back of the classrooms to minimize disruption to ongoing classes and reduce the likelihood of children tampering with the equipment.

An additional measuring station was attached to the façade of one of the school buildings to log local outdoor conditions. Finally, an observation log to document classroom and sensor information was filled at each classroom, along with photographs documenting the classroom environment and systems. A sample observation log used in this research can be found in Appendix A.

2.3.2.2. Surveys

Surveys can be used as diagnostic tools, offering detailed insights into a building's day-to-day operation through occupant feedback. The questionnaire used in this methodology drew its structure from multiple specialized sources, including the satisfaction survey from standard ASHRAE 55 used for long-term thermal comfort assessment (ASHRAE, 2017), the MM-040 questionnaire from the Örebro Model (Andersson, 1998), and other research looking into occupant satisfaction with indoor environmental quality conditions (Graham et al., 2021; Kwok, 1997).

The survey is exclusively aimed at teachers and encompassed eight blocks of questions that cover perceptions of the school's general environment, thermal comfort, and indoor air to understand the school's IEQ. In addition, it included a block on maintenance awareness, which aimed to understand the teacher's relationship with the school's facility and management. Since the survey was developed post-pandemic, it also included a section on COVID-19 protocols during and after the pandemic. The survey had a block with health-related questions, controlling for past respiratory health problems and influences and inquiring about current symptoms. Finally, the survey included blocks of questions controlling for acoustic and lighting perceptions, which might influence other environmental perceptions (Table 2-3). A detailed sample of the survey questionnaire can be found in Appendix B of this document.

Surveys were administered during the same week as physical measurements to allow for correlations between short-term environmental perceptions and measured outdoor parameters. The surveys were answered by a representative sample of teachers, with the number varying depending on the school's size.

All elementary teachers were invited to a meeting to answer the survey to gather as many responses as possible, and participation was voluntary. Following the ASHRAE 55 approach, 15 occupants should answer surveys when between 20 and 45 occupants are asked to respond. If fewer respondents are available, at least 80% of the occupants should complete the survey (ASHRAE, 2023b). In the case studies covered in this document, the researchers aimed to have all teachers respond simultaneously during a single meeting to ensure a significant number of responses. However, if this was not feasible in a school, the survey link was distributed via email, although this made it more challenging to control the timing and number of responses. This approach proved a lot less effective, and fewer responses were received. Person to person contact during the meeting allowed for a better explanation of the project, created a rapport between the researcher and the participants, and gave teachers enough time to respond to the survey and ask questions if necessary.

Table 2-3 Summary of question blocks and measures of the survey

Question block	Measures
Basic information	Permanence in classrooms
General School Environment	Comfort on multiple IEQ parameters, IEQ issues frequency, outdoor air long-term acceptability, outdoor air acceptability frequency
Maintenance Awareness	Systems awareness and use, IAQ protocols during COVID-19 and post COVID-19, student complaints, personal adaptations to the environment
Ventilation and IAQ	Outdoor air short-term acceptability, indoor air short-term acceptability, IAQ satisfaction, indoor air problems concern
Thermal comfort	Thermal sensation, thermal preference, thermal satisfaction, thermal problems concern
Health	Potential environmental health influences, previous respiratory health problems, smoking history, current respiratory health symptoms
Acoustics, lighting, cleaning	Acoustic problems, lighting problems, and general cleaning problems
Demographics	Demographic information

2.3.2.3. Interviews

Interviews are targeted qualitative sources of evidence that can provide insights, explanations and personal views about a phenomenon (Yin, 2018). The methodology used semi-structured interviews to gather in-depth information from teachers and facility managers. Teachers who stay in the same classroom most of the time can provide detailed information about its indoor environment, while facility managers can give insights into the maintenance and operations practices of the school. The data collected through interviews is key to addressing relationships between occupants and management, and management and building shown in Figure 2-1.

In all cases, the teachers that usually stay in the classrooms where the physical measurements occur were the ones who participated in the interviews. This allowed for the association of classroom conditions with the teachers' testimony. Interviews were usually done outside of the class schedule and took less than 30 minutes to avoid interviewee-fatigue and scheduling difficulties. The researcher included follow-up questions and probes to the basic questions where possible to expand on teachers' answers (Table 2-4).

Not all school districts work in the same way, so it was important to connect with key maintenance and operations personnel. These interviews took up more time since this was the primary source of information about maintenance practices, and in some cases, there was only one manager per multiple schools. The questions in Table 2-5 were intended as a guide and were adjusted for each case. For example, the mechanical systems questions were not applicable in naturally ventilated schools. In such cases, the researcher adapted the questions to focus on general maintenance practices. Furthermore, certain questions were not suitable for all participants, depending on the specific maintenance structure of a school. Consequently, the researcher customized the interview based on the characteristics of each school or district. All interviews were recorded and transcribed for the analysis phase.

Table 2-4 Teacher interview questions

Data aimed to collect	Question
Personal experience	Could you tell me about your teaching experience at this school? Could you describe a typical day for you at school?
Maintenance awareness	Could you describe any current school protocols or maintenance practices that you know of that would maintain the classroom air and temperature comfortable? Were the protocols different in the past 3 years? How? Describe the changes that the school has made during the last few years to improve air quality and thermal conditions of the classroom.
Comfort Perceptions	How does the temperature and air in your classroom typically feel?
Environmental controls and influences	Could you describe how you control the heating, cooling, and ventilation of air in your classroom? Do you ever hear complaints from your students regarding temperature or air inside the classroom? Which? Do you think the environmental conditions of the classroom influence your students' learning? How? Is there anything that you have done personally to maintain or improve the air quality or comfort in your classroom?
Preconceptions and preferences	What do you consider the most important factors to a comfortable and healthy classroom environment? What would you change in the classroom to improve your environmental comfort?

Table 2-5 Facility maintenance interview questions

Data aimed to collect	Question
Personal experience	What is your role in this school or district?
Maintenance & budget	Does this school/district have a maintenance plan? How is maintenance carried out? How do you inspect and diagnose the school facility to determine the need for maintenance? What percentage of your funding is budget for maintenance and major system replacement? How do you manage and schedule your budget spending to carry out the school maintenance? What are the biggest challenges for carrying out maintenance?
Maintenance practices & documentation	Which maintenance practices provide the most benefit? Describe any upgrades/modernizations made to the system in the last few years How often do you maintain the HVAC system and/or other systems in the school? In your experience, how are the mechanical systems in the school/district performing? How are the various maintenance practices documented?
Environmental controls and operation	*Mechanical systems* What practices does the school/district have for HVAC systems? Describe the system used in this school or the schools you manage What is the HVAC schedule for a typical school week? How are the environmental conditions controlled in the classrooms? Are there any situations where teachers can change the conditions? *Natural ventilation* Do the classrooms have operable windows? Why or why not?
Occupant interactions	How often does your office receive complaints or requests about TC or IAQ? How do you typically handle these complaints? How do you engage with occupants about maintenance practices and receiving services? Describe any practices, if you know of any, that the staff or community has taken upon themselves to improve indoor environmental quality.
Preconceptions and preferences	What would you identify as strengths and weaknesses of the maintenance and operations of this school/district? If funding were unlimited, what would you like to see happen in your school?

2.3.3.Data analysis

For the quantitative portion of the case studies all data was cleaned before starting the analysis. This involved removing sensor measuring errors, incomplete data and averaging the measurements to a desired time interval. Then, new databases were constructed including data from multiple sensors for further analysis. Basic graphic representations and descriptive statistics allowed for a preliminary study of the data. Also, comparing the physical measurements with the existing standards provided an initial assessment of classroom environmental performance. Other helpful approaches included looking at the weekly trends in each classroom and creating a data analysis plan for relevant occupancy periods, variables to study, and statistical tests to use. Multiple analyses can be drawn from the physical measurements, so the data was mined considering the variables relevant to each case, and the research goal of each chapter.

The qualitative analysis, HyperResearch software was used to code respondents' testimonies. These codes were organized into themes and cross referenced to create a narrative around the relationships described in Figure 2-1. Given the exploratory nature of the method, unexpected themes emerged by finding patterns, insights and concepts in the interview transcriptions. Insights stemming from the qualitative data provided complementary information to the quantitative data. Therefore, the results from each method were presented independently first, and then were used jointly to create a narrative for the case study. This inductive approach facilitated a comprehensive exploration of the research question by considering the relationships from multiple angles, allowing for themes and additional insights to naturally emerge from the data.

2.3.4.Application and validation

The methodology was applied and refined in multiple case studies conducted in twelve schools across three school districts in Southern California, one school in Oregon, and three Concepción, Chile, which are presented in this document. The protocol was translated and adjusted to fit the unique circumstances of each case, as each location has a different context, climate, ventilation type and facility management system.

The application occurred over a week in each school during the most extreme season of the year when classes were in session. This approach aimed to gain insights into the most critical IEQ issues that schools might encounter. Consequently, the methodology was applied in the summer in California, between spring and summer Oregon, and during the winter in Concepción, offering insights into the specific circumstances and contexts of each location. All the selected case studies were public, low socioeconomic status schools. In this way, despite contextual differences, there was a common type of school across countries. In addition, all the selected classrooms were elementary school classrooms, where the same teacher stays in the classroom all day, providing uniformity for the interviews and physical measurements setup. The survey process proved more efficient when conducted in person compared to email distribution. In-person sessions facilitated participant inquiries and ensured a higher response rate. The number of responses also varied based on the school's size, a crucial factor to consider during data triangulation.

The methodology exhibited flexibility in accommodating various school maintenance and operations organizational structures, offering a comprehensive understanding that yielded valuable insights from each case. Nevertheless, further inquiry was necessary in each location to comprehend the specific structure and regulations, and to establish contact with the relevant personnel. By addressing the same measures using multiple sources of evidence, the methodology was able to construct validity by generating converging sources of information suitable for triangulation. Given that it is a case study approach, the primary aim was to achieve a holistic explanation rather than one based on variables.

It is important to note that the qualitative portions of the methodology brought about new themes that are seldom introduced in thermal comfort and IAQ studies, which include local policies and negotiations between different stakeholders, teachers' beliefs, the impact of personal histories and socioeconomic status on thermal preferences, the influences of teaching practices on environmental adaptations, the impacts of maintenance management of classroom conditions, among others. All these topics are deeply intertwined with how environmental conditions in classrooms are constructed and provide a fresh look into thermal comfort and IAQ studies.

2.4. Conclusions

This chapter presents the methodology used to inquire on the influences of indoor air quality and thermal comfort in schools. The methodology starts from the proposition that current approaches to study this topic do not address the causes and mechanisms through which adequate IEQ conditions occur in classrooms. Therefore, it investigates multiple interactions that occur between the building (classrooms), the occupants (teachers), and the facility maintenance and operations (managers and maintenance personnel) to render adequate IAQ and thermal conditions in classrooms. To sort out these interactions, the methodology relies on the analysis and triangulation of multiple sources and types of data.

The methodology proposes a mixed-methods research approach that includes documentation on the building and context, physical measurements of the environment, surveys, and interviews with key stakeholders. These methods aim at gaining a comprehensive view on the influences of IEQ in schools, which is not possible to achieve solely through quantitative methods. By integrating qualitative methods and adopting an inductive approach, the methodology aims to derive conclusions that extend beyond physical measurements and acknowledge the human influences in the operation of schools that contribute to creating optimal indoor environments in classrooms and providing comfort for building occupants.

2.5. Strengths and limitations

This methodology prioritizes qualitative data and introduces new stakeholders to the investigation of IAQ and thermal comfort. Its main limitation is its inability to extrapolate findings across cases, given its mixed-method nature. Instead, it seeks to achieve an in-depth understanding of each case, and extract insights on the mechanisms and interactions contributing to the creation of indoor environmental conditions in each school. Therefore, the conclusions from each case are specific to each location, and the lessons learned may serve to inform other cases elsewhere in the form of theories, but not generalizations.

Through the testing and validation process, the methodology proved flexible for its application in multiple locations. It can incorporate multiple contextual variables, seasons, and types of schools. Nonetheless, the questionnaires may need to be slightly adjusted in the cases in which interview or survey questions don’t

apply directly to a particular case. These adjustments might represent a challenge during the analysis phase and might complicate the presentation of the results in a uniform manner.

Finally, the methodology builds its robustness through the triangulation of data from multiple sources. Working with large amounts of data of different kinds can prove complicated and overwhelming, so the effectiveness of the method largely depends on the analytic capacities of the researcher and their approach in the data analysis. While the research instruments can be standardized, the qualitative analysis still largely depends on the researchers' coding of the data, which can vary from person to person. Nonetheless, the diversity of data sources, the initial research framework, and aligning the data collected through quantitative and qualitative methods contribute to constructing the methodology's internal validity.

2.6. Bridge

This chapter presented a methodology to investigate thermal comfort and indoor air quality in school facilities through case study research, using a mixed-method approach. This is the baseline upon which the rest of this document is built. The following chapters present explorations of the application of this methodology in various case studies, focusing on one or multiple methods and/or topics that arose in each case study. Chapters 3 and 4 use partial data gathered through the methodology in the Oregon and Chilean cases, while Chapters 5 and 6 present the California case study involving the entirety of the gathered data.

3. A Pilot Study on Indoor Air Quality in a Naturally Ventilated Classroom in Eugene, Oregon, During the COVID-19 Pandemic

Coronado, M.C., and Kwok, A. (2023). A Pilot Study on Indoor Air Quality in a Naturally Ventilated Classroom in Eugene, Oregon, During the Covid-19 Pandemic. In conference proceedings: ARCC International Conference: The Research-Design Interface. Dallas, April 12-15, 2023.

The case study described in this chapter was developed in co-authorship. It was conceptualized, developed, written and reviewed by Maria C. Coronado, with reviews and revisions by Alison Kwok.

3.1. Introduction

Schools constitute the second place where children spend more time after their homes. Therefore, they are important contributors to children's health and well-being. This is relevant, as research has shown that children are more vulnerable than adults to poor indoor air quality (IAQ) because they are more sensitive to cold, heat and moisture, and breath more air per weight than adults (Sadrizadeh et al., 2022). In addition, ventilation plays a role in children's academic performance. For instance, a meta-analysis found evidence that students in classrooms with higher ventilation rates and lower CO_2 concentrations perform better on standardized tests and performance tasks by as much as 15% (Fisk, 2017). However, before the pandemic multiple research studies found that classrooms usually did not meet the minimum ventilation rates specified by the existing IAQ standards, and did not provide adequate air quality to students (Daisey et al., 2003; Shendell et al., 2004; Wargocki & Wyon, 2013).

Ventilation is also important to dilute air pollutants. Multiple pollutants of chemical and biological origin have been identified in schools, including particulate matter, fungi, pollen, bacteria, viruses, mites, NO_2, CO, and VOCs (Mendell & Heath, 2005; Sadrizadeh et al., 2022). These pollutants have been correlated with an array of health symptoms in children (Daisey et al., 2003; Marcotte, 2017), and measures of school absenteeism (Mendell & Heath, 2005), but more research is necessary to understand their direct physiological impacts within given levels of exposure in school settings.

During the COVID-19 pandemic, increasing ventilation rates was one of the main strategies to prevent the spread of the virus and to create safer environments. To do this, many school districts prioritized upgrading their ventilation and filtration systems and/or installed new windows in their schools. In 2020, the U.S. Government Accountability Office (GAO) estimated that in about 41% of public school districts, at least half the schools needed to upgrade their HVAC systems (U.S. Government Accountability Office, 2020). In fact, the top challenge for schools to implement the recommended IAQ measures during the pandemic was that their HVAC systems were not designed to handle such high ventilation rates (The Center for Green Schools & ASHRAE, 2021). For schools that could enhance ventilation, increases in energy demands resulting from intensifying outdoor air intake in HVAC systems became a common tradeoff (The Center for Green Schools & ASHRAE, 2022). Also, in naturally ventilated schools operating during the pandemic, there was an additional issue with decreased thermal comfort, especially during the winter months (Alonso et al., 2021; Miranda et al., 2022).

Multiple guidelines were developed during the pandemic to assess indoor air quality in schools. In the U.S., some of the most salient recommendations came from the Centers for Disease Control and Prevention (CDC), American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), Harvard's T.H. Chan School of Public Health, the Center for Green Schools, and the National Academies of Sciences, among others, shortly after the pandemic started. These guidelines used CO_2 concentrations as a proxy to assess ventilation and provided recommendations to evaluate and improve ventilation and filtration inside school buildings. Later, in February 2022, ASHRAE released its position document on indoor CO_2. In this document, they clarified some of the existing misconceptions about CO_2 concentrations and their relationship with ventilation rates. Previous studies often used 1000 ppm and 700 ppm as direct indicators of adequate ventilation in classrooms. However, these values are not included in the current ANSI/ASHRAE Standard 62.1-2022, Ventilation and Acceptable Indoor Air Quality, because their use has often been misinterpreted. These values are linked to building occupants' perception of human body odor, not ventilation needs for healthy indoor air. Using CO_2 as an indicator of the outdoor ventilation needs of a space requires the inclusion of other considerations such as the space type, occupant density, and occupant characteristics like age, body mass, and activity levels (ASHRAE, 2022b).

Particulate matter (PM) is also a significant concern for student and teacher health. PM is a mixture of different pollutants of chemical and biological origin that can infiltrate the respiratory system. Particles of

less than 2.5 µg/ m^3 (respirable) can infiltrate the gas-exchange region of the lungs, while particles of less than 10 µg/ m^3 (inhalable) can be hazardous when deposited in the respiratory tract (Morakinyo et al., 2016). In school facilities, PM may come from indoor or outdoor sources. Indoor sources may include chalkboard dust, resuspended dust from children's activity, cleaning, and combustion sources for heating, while outdoor sources may include traffic, wildfires, or industrial emissions. Outdoor sources are usually more problematic in urban areas (Sadrizadeh et al., 2022). The potential health effects of PM are highly related to the level of exposure and the surface area, size, mass, and composition of the particles, which determines their toxicity (Morakinyo et al., 2016). For example, previous studies reported reduced lung function, asthma, and other pulmonary diseases in children and adults exposed to high levels of endotoxins present in PM (Morakinyo et al., 2016). Similarly, other studies have found links between $PM_{2.5}$ exposure with symptoms of conjunctivitis, hay fever, itchy rash, and sensitization to outdoor allergens in children (Sadrizadeh et al., 2022).

The Air Quality Index (AQI) is one of the U.S. Environmental Protection Agency's (EPA) tools for communicating daily outdoor air quality. The AQI is directly related to health, as its purpose is to inform people about the air quality so that they can take steps to protect their health. The AQI reports mean values for exposures to multiple pollutants, including O_3, CO, SO_2, and NO_2, in addition to $PM_{2.5}$ and PM_{10}. For PM, the index considers concentrations and periods of exposure of 24 hours. These times may be modified if the air quality changes rapidly during a critical event, like a wildfire (United States Environmental Protection Agency, 2018).

This study was developed at the end of the pandemic during a week of class in the Spring of 2022. The study aimed to characterize and evaluate the indoor air quality performance of a fully naturally ventilated classroom in Eugene, Oregon, with all the school ventilation protocols put in place. The pilot included physical measurements of CO_2 and PM concentrations and additional environmental parameters such as indoor and outdoor temperature and relative humidity. In addition, classroom occupancy and window and door operations were recorded to correlate the indoor environmental conditions with users' behaviors.

3.2.Methodology

3.2.1. The setting

The pilot study was conducted in an elementary school classroom in Eugene, Oregon, without significant sources of pollution in its surroundings, during the end of the spring of 2022. The school didn't have any. The classroom dimensions were 8.4 m (27.5 ft) wide x 12.2 m (40 ft) long x 3.3 m (11 ft) tall, with 3.3 m (11 ft) x 3.3 m (11 ft) bathrooms in the back of the classroom. The classroom had hard-tile flooring in the back half portion of the classroom and carpet in the front half. Under maximum occupancy, the classroom had 23 students and a teacher.

Conversations with the teacher and the school administration helped to determine classroom occupancy and usage. The teacher arrived at the classroom around 8:00 am each day. Then, students entered the classroom at 8:15 am and left at 2:50 pm. Recess periods occurred from 9:45 am to 10:00 am and 11:45 am to 12:05 pm and were held outside the classrooms, except during critical air events like wildfires. Classrooms were not always occupied during class periods as students had specialty classes in other classrooms or additional periods of outdoor work. While students were in their specialty classes, teachers stayed inside the classroom working. After the students left, the teacher stayed in the classroom until 5:30 pm, working alone. When the teacher left, the classroom remained unoccupied until the evening. Then, the custodian entered the classroom to clean and vacuum the floors for about 15 minutes between 7:00 and 8:00 pm. In addition, every Friday afternoon, a group of volunteer parents helped to thoroughly clean and sanitize the classroom moving the furniture and wiping all the desks.

The classroom was entirely naturally ventilated and had a ductless mini-split unit in the back for heating and cooling. The classroom had windows and doors on opposite sides that led directly to outdoor spaces. The east side of the classroom led directly to a garden and had 7 fixed windows plus 3 operable awning windows and 1 door. The west wall contained 5 windows and the front door, which was the main entrance to the classroom, leading to an open courtyard. On this side, only the middle window was an operable single-hung window. All windows on the west wall of the classroom were built during the pandemic, including the operable window to create cross-ventilation inside the classroom and increase the ventilation in the room (Figure 3-1).

During the study period, the school had ventilation protocols put in place. After the teacher arrived in the classroom, she placed a fan in the single-hung window and turned it on to exhaust the indoor air and create a cross-ventilation flow. The teacher would also open all awning windows and crack open the garden door shown in Figure 3-1A. This setting stayed constant all day, so the main adaptation for indoor air came from opening and closing the front door during the day. At the end of their workday, the teacher turned off and removed the fan from the window, closed all windows and doors, and left the classroom. During the study, all students were wearing masks all through the day.



Figure 3-1(A) Classroom interior and windows overlooking a garden (B) Front of the classroom with box fan for air circulation

3.2.2. Physical measurements and occupancy logs

During the study period, a sensor station was placed near the teacher's desk in the front of the classroom. Sensors were calibrated according to the manufacturer's recommendations prior to the start of the study. Indoor environmental parameter readings were collected every 5 minutes for a week. Measurements included readings of indoor and outdoor particulate matter (PM) at 2.5 µg/ m^3 and 10 µg/ m^3 and indoor CO_2, temperature, and relative humidity. Outdoor CO_2 measurements were taken using a handheld sensor near the school on the last day of the study, and then averaged and taken as constant for the ventilation

calculations. All outdoor readings were collected from an existing Purple Air sensor one block from the school. Table 3-1 summarizes the sensors and measurements used in the study.

Table 3-1 Sensors and measurements used for the study.

Sensor	**Measurement**	**Precision**
HOBO MX1102 CO_2 logger	CO_2 (ppm)	0 to -5000 ppm. ±50 ppm ±5% of reading at 25°C (77°F), < 90% RH (non-condensing) and 1,013 mbar
	Temperature (ºC or ºF)	0° to 50°C (32° to 122°F). ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F)
	Relative humidity (%)	1% to 90% R.H. (non-condensing). ±2% from 20% to 80% typical
Dylos air quality monitor DC1700 – PM	$PM_{2.5}$ and PM_{10}	Particle concentration (>0.5um,>2.5um) or mass concentration in $PM_{2.5}$ / PM_{10} (μg / m^3)
TSI 9565 plus 982 IAQ probe	CO_2 (ppm)	0 to 5000 ppm CO_2 ±3% of reading or ±50 ppm CO_2, whichever is greater.
Purple Air outdoor sensor	$PM_{2.5}$ and PM_{10}	Counting efficiency 50% at 0.3μm & 98% at ≥0.5μm. Effective range ($PM_{2.5}$ standard): 0 to 500 μg/m^3

In addition to physical sensing, a camera was directed at the windows and doors of the classroom. The camera was configured to take a picture when it detected movement. This allowed for a detailed recording of the window status (open or closed) and detailed tracking of the classroom occupancy without interfering with the classes. These records were complemented by conversations with the teacher to trace classroom occupancy patterns.

3.3.Results

3.3.1. Indoor/outdoor air relationships

Indoor and outdoor levels of particulate matter, CO_2, temperature, and relative humidity were recorded during the study period. Since the classroom is naturally ventilated, we expected significant correlations between indoor and outdoor environmental parameters. Indoor temperatures had an average of 19.3 ºC (66.7 ºF) and a 50.5% relative humidity, while the mean outdoor temperature was 16.4 ºC (61.5 ºF) with 56.82% relative humidity.

To understand the relationships between indoor and outdoor air quality variables, a correlation analysis was used. Since PM and CO_2 measurements did not meet the normality assumption, we used Spearman's rank-order correlations to assess these relationships. Since outdoor CO_2 was measured and averaged into a constant value of 425 ppm, it was not included in the correlations. Table 3-2 shows the correlation coefficients between indoor and outdoor measurements for relevant air parameters. As expected, all indoor and outdoor parameters were significantly correlated between themselves at the $p < 0.01$ level. However, indoor PM_{10} and $PM_{2.5}$ concentrations did not correlate significantly with outdoor PM_{10} or outdoor $PM_{2.5,}$ implying additional PM sources inside the classroom.

Indoor $PM_{2.5}$ had a maximum concentration of 99 μg/ m^3 and an average of 7.89 μg/ m^3. This average concentration is in the "good" category for the pollutant-specific sub-indices in the Air Quality Index (AQI) of the Environmental Protection Agency (EPA) (United States Environmental Protection Agency, 2018). Outdoor $PM_{2.5}$ had an average concentration of 1.85 μg/ m^3 and a maximum of 11.54 μg/ m^3, implying that indoor $PM_{2.5}$ levels were higher than outdoor levels during the study period. Similarly, indoor PM_{10} concentrations had an average of 28.40 μg/ m^3 and a maximum of 1227.9 μg/ m^3, while outdoor PM_{10} concentrations reached a max value of 15.53 μg/ m^3 and had an average concentration of 2.3 μg/ m^3. These average concentrations also fall into the "good" category of the AQI for PM_{10} and show a similar trend, where indoor PM concentrations are higher than outdoor ones. Indoor CO_2 concentrations reached a maximum value of 778 ppm during the study period and an average of 520.68 ppm.

Table 3-2 Correlations between measured indoor and outdoor environmental parameters

		Indoor			Outdoor	
		CO_2 (ppm)	$PM_{2.5}$ (µg/ m^3)	PM_{10} (µg / m^3)	$PM_{2.5}$ (µg / m^3)	PM_{10} (µg/ m^3)
Indoor	CO_2 (ppm)	520.68 (50.276)				
	$PM_{2.5}$ (µg/ m^3)	0.227**	7.888 (7.392)			
	PM_{10} (µg/ m^3)	0.250**	0.918**	28.399 (65.21)		
Outdoor	$PM_{2.5}$ (µg/ m^3)	0.144**	-0.032	0.033	1.854 (2.327)	
	PM_{10} (µg/ m^3)	0.169**	-0.034	0.024	0.988**	2.307 (2.656)

Means and standard deviations (in parentheses) are displayed on the main diagonal.

**Indicates significance at the $p < 0.01$ level.

3.3.2. Influences of occupancy and behavior on indoor air quality

To understand the relationships between occupancy and the measured indoor air parameters, five different types of occupancy were characterized during the study according to the number of occupants in the classroom and their activities. Table 3-3 shows the different types of occupancy recorded during the study period. Particulate matter and CO_2 concentrations fluctuated throughout the day and were closely related to occupancy. A visual inspection of the boxplots showing PM and CO_2 concentrations in different occupancy types revealed that the distributions were not similar (Figure 3-2 to Figure 3-4). Therefore, Kruskal-Wallis non-parametric tests were carried out to examine the differences between the occupancy type and the indoor PM and CO_2.

The test showed significant differences in $PM_{2.5}$ concentrations under different occupancy types $\chi 2(4) = 460.24$, $p < .001$. Pairwise comparisons were performed using a Bonferroni correction for multiple comparisons. Adjusted p-values are presented. $PM_{2.5}$ concentrations in unoccupied conditions (mean rank = 414.42) were significantly different from all occupancy types: low (mean rank = 768.64, $p < 0.001$), high (mean rank = 896.78, $p < 0.001$), clean (mean rank = 927.11, $p < 0.001$) and high cleaning (mean rank = 996.63, $p < 0.001$). Therefore, PM values were significantly lower when the classroom was empty than in all other occupancy types. In addition, cleaning and high cleaning periods when parents helped clean the classroom had the highest mean ranks, implying that this is when the highest $PM_{2.5}$ concentrations generally occurred.

Following the same design, a Kruskal-Wallis test was run for PM_{10} concentrations for all occupancy types, and significant differences were found between occupancy types $\chi 2(4) = 4574.51$, $p < .001$. Following pairwise comparisons using Bonferroni revealed a similar trend to the one found with $PM_{2.5}$. Significant differences in PM_{10} concentrations occurred between unoccupied conditions (mean rank = 401.36) and all other occupancy conditions. The mean ranks for each occupancy condition are as follows: low (mean rank = 740.65, $p < 0.001$), high (mean rank = 973.54, $p < 0.001$), clean (mean rank = 993.43, $p < 0.001$), and high cleaning (mean rank = 1067.25, $p < 0.001$). All mean ranks were higher than the mean rank in unoccupied conditions, implying that PM_{10} concentrations were generally higher when the classroom was occupied. Notably, the highest mean ranks occurred during cleaning and high cleaning periods.

Table 3-3 Typical occupancy types and activities related to each occupancy type during the study.

Occupancy Type	Occupancy description	Activity
Unoccupied	No occupants	NA
Low	1 adult	Reading, writing, sitting.
High	23 children and 1 adult	Classes, reading, writing. Usually sitting on desks or on the floor.
Cleaning	1 adult	Vacuuming, walking.
High cleaning	8 adults	Cleaning and disinfecting the classroom. Moving furniture.

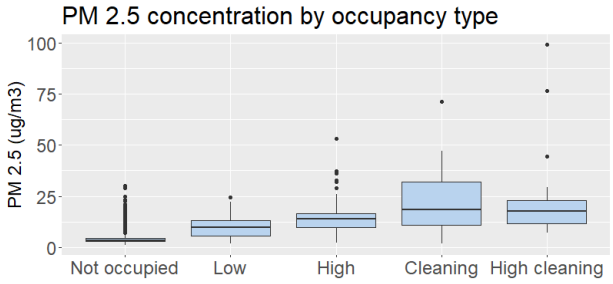


Figure 3-2. $PM_{2.5}$ concentrations in $\mu g/m^3$ by occupancy type.

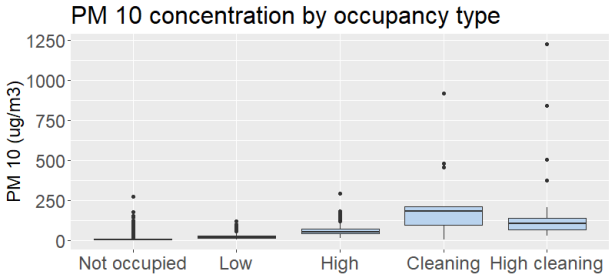


Figure 3-3 PM_{10} concentrations in $\mu g/m^3$ by occupancy type.

Indoor CO_2 is usually used to indicate occupancy, but its concentrations vary depending on activity levels and occupant characteristics (ASHRAE, 2022b). Therefore, a Kruskal-Wallis test was run to determine if there were significant differences in CO_2 concentrations between the 5 occupancy types. The distributions of CO_2 concentrations were statistically significantly different between groups, $\chi 2(4) = 357.78$, $p < .001$. Post hoc analysis revealed that CO_2 concentrations in all occupancy types were significantly different from high occupancy conditions (mean rank = 988.16) ($p < 0.001$). Statistically significant differences also occurred in CO_2 concentrations between low occupancy (mean rank = 375.90) ($p < 0.001$) and unoccupied (mean rank = 532.72) and high cleaning conditions (mean rank = 672.79). In contrast, no significant differences were found between unoccupied and cleaning or high cleaning conditions. In addition, the low occupancy mean rank was the lowest among all occupancy types, implying that an additional factor was causing a decrease in CO_2 concentrations under low occupancy (Figure 3-4).

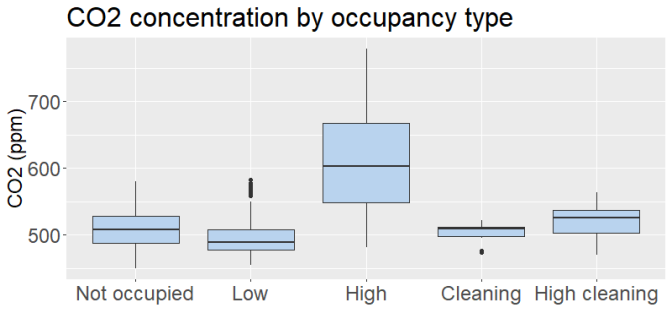


Figure 3-4 CO_2 concentrations in ppm by occupancy type.

To further investigate the influences of behavioral adaptations on CO_2 concentrations, Mann-Whitney tests were carried out to compare CO_2 concentrations with the front door open and closed, as this condition changed multiple times during the day. Opening and closing windows was discarded, as they were in the same position during all the periods when the classroom was occupied. In addition, since the door was never closed during cleaning or high cleaning periods, these comparisons are not presented here. Average CO_2 concentrations with the door open during high occupancy were 565 ppm and 625 ppm with the door closed.

Distributions of CO_2 concentrations were not similar, as assessed by visual inspection, so only mean ranks are compared here. In high occupancy, CO_2 concentrations were significantly different with the door open

(mean rank = 53.12), and the door closed (mean rank = 96.69), U = 1368.500, z = -5.212, p <0.01 (Figure 3-5). In low occupancy, there was no significant difference between the distributions of CO_2 concentrations when the door was opened compared to when the door was closed (Figure 3-6). Therefore, opening the door had a significant influence when the classroom was in full occupancy.

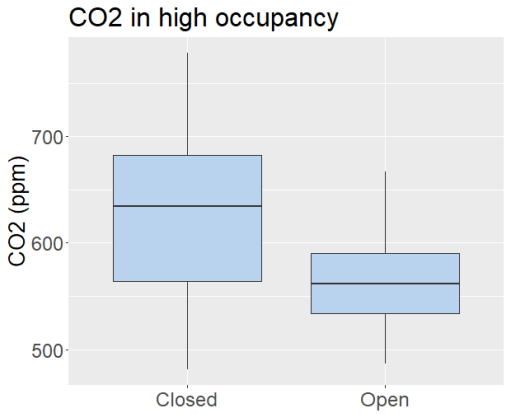


Figure 3-5 CO_2 concentrations in ppm with the front door open and closed during high occupancy.

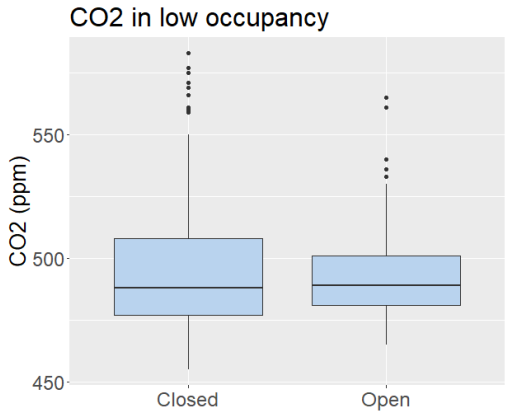


Figure 3-6 CO_2 concentrations in ppm with the front door open and closed during low occupancy.

3.3.3. Indoor air quality according to pandemic recommendations

To test whether the indoor CO_2 levels of the classroom complied with recommendations developed during the pandemic. The ventilation rates were estimated using the 5-step guide to checking ventilation rates in classrooms developed by the TH Chan School of Public Health (Allen et al., 2020). The selected procedure is meant to work with any type of ventilation system and only requires a CO_2 monitor. This procedure renders an estimation of the indoor CO_2 concentration for a desired ventilation rate, which can then be compared with the on-site measured CO_2 concentrations.

For this analysis, only the concentrations measured during high occupancy were included, as these are the ones that are of interest. The outdoor CO_2 concentration used was 425 ppm, which is slightly higher than the usual value of 400 ppm, as mentioned by the guide. The per-person CO_2 generation rate for children was 0.0066 and 0.013 for adults. The estimated CO_2 concentration targets for the classroom were 3 ACH (697 ppm), 4 ACH (629 ppm), 5 ACH (588 ppm), and 6 ACH (561 ppm). During the pandemic, 6 ACH

were considered “ideal,” 5 ACH “excellent,” 4 ACH “good,” and 3 ACH the “bare minimum.” The average CO_2 concentration measured during the study period was 521 ppm, and during high occupancy, it was 608 ppm, which would place the classroom between 4 and 5 ACH at different moments. With the door open, the mean CO_2 concentration during high occupancy was (565 ppm), which is close to the 6 ACH ideal.

Carbon dioxide concentrations fluctuated during the day. Figure 3-7 shows the frequency of CO_2 concentrations measured during high occupancy periods, and the estimated targets for different ACH calculated with the TH Chan guide. When comparing the actual CO_2 concentrations with the estimates during high occupancy periods, the classroom was above 3 ACH 88.1 % of the time, above 4 ACH in 59% of the readings, above 5 ACH 42.26% of the time, and only above 6 ACH in 30.3% of the readings.

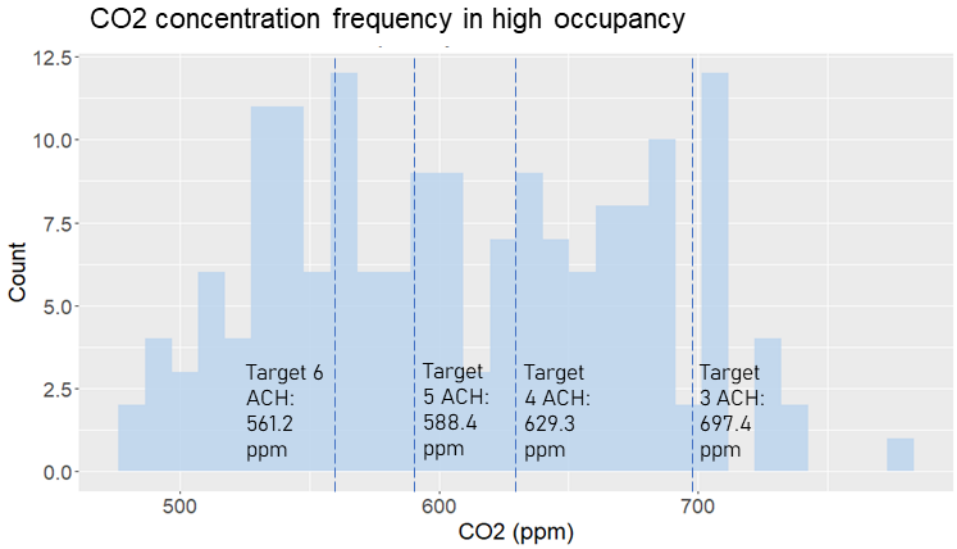


Figure 3-7 Frequencies of CO_2 concentrations in high occupancy.

3.4.Discussion

The measurements revealed that despite being entirely naturally ventilated, the PM concentrations inside the classroom were not correlated with outdoor values. Instead, variations in PM depended on the activity inside the classroom. In this case, the periods when the custodian or a group of volunteer parents sanitized

and helped deep clean the classroom registered higher PM concentrations for brief periods of time. Nonetheless, the mean air quality of the classroom remained under good conditions according to the air quality index of the EPA for $PM_{2.5}$ and PM_{10}. Other studies have shown that high outdoor pollutants are the leading cause of adverse IAQ (Raysoni et al., 2011). For example, in other studies, road traffic or outdoor pollution has been highly correlated with poor indoor air quality (Mendoza et al., 2021). In this study, outdoor PM levels were benign, so increases in indoor PM levels were mainly dependent on classroom cleaning activity. Replication of the study and measurements over more extended periods, including critical, seasonal events such as wildfires or in denser urban locations, could provide a broader range of situations to understand the performance of the building under different outdoor PM concentrations.

For CO_2 levels, it was not the activity but the number of occupants and their adaptive behaviors that drove the differences in concentrations. As expected, during high occupancy periods, CO_2 concentrations were higher, and in periods when windows were closed, and no-one was inside CO_2 levels were low. Nonetheless, during low occupancy periods, CO_2 concentrations were lower than when the classroom was empty. One possible explanation for this is that during low occupancy, all windows remained open, and the fan was turned on, continuing to flush CO_2 outside the classroom. In contrast, most unoccupied periods represented late afternoon and nighttime when the windows and doors were closed, and the fan was turned off. Therefore, the CO_2 was confined to the classroom until the teacher returned in the morning. Opening all windows and doors without occupants inside the classroom at the end of the day or before classes may be a good strategy to start the day with CO_2 concentrations matching outdoor values.

Assessing the differences in CO_2 concentrations in high occupancies with the front door open or closed showed the effects of adaptive behaviors in classroom ventilation. With the door open, the CO_2 concentrations were significantly lower than when the door was closed, reaching mean CO_2 concentrations close to the recommended 6 ACH. Since cross ventilation fluctuates throughout the day, it is not possible to always ensure consistent ventilation rates. Other ventilation strategies like stack ventilation could provide ventilation more consistently since they don't rely on wind. Classroom ventilation could be complemented with portable air cleaners with HEPA filters to increase safety when ventilation is low (Allen et al., 2020). The results of this study show how adaptive behaviors and ventilation protocols are key in maintaining an adequate indoor air quality in naturally ventilated indoor spaces. Good ventilation may be achieved using low-tech means under good outdoor conditions. The

results also show that on average, and during mild seasons like the spring, natural ventilation might be able to provide adequate ventilation rates for classrooms. In more extreme seasons like the winter, other strategies such as Stosslüftung (shock ventilation) may be useful. During Stosslüftung, windows are fully opened for several minutes taking a small thermal comfort penalty but improving indoor air quality and providing more air changes per hour.

The study showed how the common assumption of maintaining classroom CO_2 levels below 1000 ppm or 700 ppm does not guarantee adequate ventilation. This value is based on the perception of human body odor and has no relation with ventilation requirements. Instead, ventilation requirements depend on space type, occupant density, and occupant characteristics (ASHRAE, 2022b). Therefore, a simple visual inspection of a CO_2 monitor in a classroom should not be taken as a definite measure of adequate ventilation. On the contrary, an estimation of ventilation rates with data on occupancy and activity type would provide a better estimate.

3.4.1. Limitations and future research

The pilot study was limited to one classroom, which did not allow for comparisons with similar spaces or other behavioral patterns. In the future, multiple classrooms could provide a wider range of data and allow for generalizable conclusions. Nonetheless, gathering data for a week allowed for understanding how the classroom worked under different occupancy conditions occurring only once a day or once a week. More extended measurement periods might provide more information on how activities, occupants, and environmental parameters change from season to season or during critical events like wildfires. In addition, it was not possible to assess the effects of window opening and closing on CO_2 concentrations since the school protocols did not allow for closing the windows while the classroom was occupied. The study also showed that in some cases, it is not the students or the teachers who control the classroom environment but the facility managers and the school administration through school-wide policy and protocols. Including other populations in this kind of research opens new opportunities, as they might provide critical information for understanding classroom performance.

Other limitations arose from the methodology and should be addressed in future iterations of the study. Only one CO_2 and one PM sensor were used and placed in one station in the front of the classroom. Since

the classroom was naturally ventilated, CO_2 and PM concentrations might have differed from other parts of the room. Previous studies have shown that CO_2 has uneven distributions in naturally ventilated classrooms, and multiple sensors may help identify these differences (D. Zhang et al., 2022). Doing this might provide better information on the classroom's ventilation rates and give an idea of which classroom areas are better mixed than others. For instance, sensors placed next to students' desks might provide a better idea of the air quality that students are breathing. Nonetheless, sensor placement might be challenging and create distractions for the students. Therefore, planning ahead and devising a non-intrusive sensor station will be critical in future versions of the study.

This study was performed during the spring; therefore, it was possible to keep windows and doors open while the teacher was inside the classroom. As schools maintain their operation during winter and summer months, continuing these behaviors may bring thermal comfort and energy use tradeoffs, as was the case for many schools during the pandemic. In addition, now that the COVID-19 pandemic has abated, it is likely that some of the protocols, behavioral patterns, and adaptations recorded during this study will rapidly change. Therefore, repeating this study in other seasons and/or climates might give better insights into how environmental parameters, behavioral adaptations, and school protocols (or their absence) affect indoor air quality in classrooms.

Finally, this study was limited to assessing only a naturally ventilated classroom. The classroom reached CO_2 concentrations close to the 6 ACH recommendation with the door open. Future studies comparing the indoor air quality of naturally and mechanically ventilated classrooms may provide insights into how occupant behaviors and school practices modify the indoor air quality of classrooms with different ventilation types. In mechanically ventilated classrooms, the air is often recirculated, which may increase indoor CO_2 and PM concentrations. In addition, a study of this kind would open other avenues of research looking into differences in energy use between ventilation strategies, as schools and districts usually have limited funding to modernize or retrofit their facilities. During the pandemic, many schools had to make great efforts to reach higher ventilation rates than what their HVAC systems provided (The Center for Green Schools & ASHRAE, 2022). Therefore, assessing the IAQ of classrooms with different ventilation types may illustrate the advantages and disadvantages of each type in school facilities.

3.5.Conclusion

This chapter presented a pilot study assessing the indoor air quality conditions of one naturally ventilated classroom in Eugene, Oregon, for a week during the spring of 2022, at the end of the COVID-19 pandemic. The study used indoor and outdoor PM and CO_2 measurements paired with recordings of occupancy and window and door opening and closing. Five occupancy types were characterized based on the number and type of occupants and their activities. In addition, informal conversations with teachers and administrative staff allowed for a general understanding of school protocols during the study period.

The results showed correlations between occupancy types and activities in the classroom with $PM_{2.5}$ and PM_{10} concentrations. In contrast, no correlations were found between indoor and outdoor PM values. According to the EPA Air Quality Index, all PM values showed good indoor and outdoor air quality conditions during the measurement period. Spikes in PM concentrations only occurred when the classroom was being cleaned and was the most impactful activity type generating additional PM concentrations in the air. Indoor CO_2 concentration depended on the number of occupants in the space and was modified by their behavioral adaptations. For example, during periods of high occupancy, CO_2 readings reached their maximum values and significantly decreased when the front door was open. In addition, CO_2 concentrations in low occupancy were lower than those in unoccupied conditions, as CO_2 remained trapped inside the classroom when the classroom was not in use.

Estimated ventilation rates evidenced the common misconception that directly measuring CO_2 in a space directly indicates adequate ventilation. When considering multiple parameters, the target ventilation rate required a lower CO_2 concentration than commonly referenced values such as 1000 ppm or 700 ppm. School protocols mandating window opening and portable fans to exhaust the air from a classroom were helpful strategies to maintain adequate ventilation rates but could not always reach the 6 ACH recommended during the pandemic. The fluctuations in ventilation rates portrayed the limitations of naturally ventilated classrooms, as ventilation fluctuated during the day. It is necessary to refine the methodology presented here and expand the study to understand better the influences of school operation protocols, behavior, and occupancy on classroom indoor air quality.

3.6.Bridge

This chapter presented a case study in a Naturally Ventilated Classroom in Eugene, Oregon, during COVID-19. The analysis was centered on particulate matter and CO_2 concentrations in the context of the pandemic. The following chapter develops a similar approach to analyze IAQ in Chilean schools but only concentrates on particulate matter pollution ($PM_{2.5}$ and PM_{10}) and includes more contextual elements. It includes the notion of energy poverty as the driver behind the findings of the case study and highlights the urgency of widespread policy changes to improve air quality in the area.

4. Air Quality and Teacher Health in the Context of Energy Poverty in Chile

Coronado, M.C., Rivera, I., Martinez, A, and Kwok, A. (2024) Air Quality and Teacher Health in the Context of Energy Poverty in Chile. Accepted for publication at EAAE/ARCC Conference 2024 - Architecture into The Unknown. Aarhus, Denmark, 23-26 May 2024.

The case study described in this chapter was developed in co-authorship. It was conceptualized, developed, written and reviewed by Maria C. Coronado, with reviews and revisions by Isabel Rivera, Andrea Martínez and Alison Kwok.

4.1. Introduction

Particulate matter (PM) is one of the classic pollutants considered hazardous by the World Health Organization (WHO). Particulate matter is classified according to size, though its chemical and physical composition might be heterogeneous (WHO, 2021). Particles less than 10 μm diameter are coarse or inhalable particles and can be hazardous when deposited in the respiratory tract. In comparison, respirable or fine particles are those smaller than 2.5 μm diameter and represent a hazard because they can infiltrate the gas-exchange region of the lungs (Morakinyo et al., 2016). Previous research has associated both $PM_{2.5}$ and PM_{10} with cardiovascular disease, lung cancer, respiratory problems, and mortality from all causes. However, the current evidence on the health effects of $PM_{2.5}$ and PM_{10} includes very limited studies done in low and middle-income countries (Chen & Hoek, 2020), where PM pollution is often a problem due to energy poverty.

For instance, in Chile, energy-poor households have been defined as those that do not have equitable access to high-quality energy services to cover the basic needs for the human and economic development of its members (Ministerio de Energia, 2021). In this sense, energy poverty can be understood as coming from three different origins 1) when energy use costs are higher than what a household income can cover, 2) when a segment of the population doesn't have access to energy services, and 3) when a dwelling's physical conditions do not provide adequate indoor environmental conditions for living (Felmer Plominsky et al., 2023). In the south-central region of the country, this has become an enduring problem,

with previous studies finding multiple municipalities at high risk of energy poverty due to heating needs (Pérez-Fargallo et al., 2020), and the high cost of electricity. In Chile, over 80% of the households in the southern areas of the country rely on firewood for heating (CDT, 2015; Reyes et al., 2019), which generates significant air pollution due to PM during the winter months. In the municipalities of Concepción and San Pedro de La Paz, 43.3% and 57.4% of households use heating with polluting sources, respectively according to official data. In addition, 50.3% of the households in San Pedro de La Paz and 56% in Concepción are thermally inefficient constructions, increasing the need for heating during the winter (Ministerio de Energia et al., 2024). To address this issue, the Chilean government has strived to reduce air pollution by creating programs for people to use dry firewood and replace wood stoves, which are still insufficient and do not fully address the root of the problem (Reyes et al., 2019).

Furthermore, while the primary source of pollution comes from residential wood stove use during the evenings and nights, the overall air quality decreases in these neighborhoods, impacting nearby public spaces and other facilities like schools. In schools, sources of air pollution can come from indoor and outdoor sources, which is particularly relevant for naturally ventilated classrooms. Some of the primary outdoor sources of PM in schools highlighted in previous literature are high traffic density, emissions from industrial areas, and wildfires. In contrast, indoor sources include chalk dust, particle resuspension due to children's activity, indoor combustion sources (heaters, gas, and wood stoves), cleaning, soil dust, new furniture, and smoking where allowed (Sadrizadeh et al., 2022).

There are many local factors affecting PM concentration levels in school buildings. For example, a study found that summer $PM_{2.5}$ and PM_{10} concentrations were up to 3 times lower than winter concentrations in a naturally ventilated school, and the authors attributed this finding to a lack of ventilation during the cold season (Habil & Taneja, 2011). Similarly, other studies have found differences between urban and rural, as well as public and private schools, depending on their immediate surroundings and indoor pollution sources (Alameddine et al., 2022; Branco et al., 2019). In addition, studies looking into social variables such as race and socioeconomic status have pointed out that higher air pollutant concentrations are associated with poverty in specific contexts (Cheeseman et al., 2022). Therefore, assessing PM concentrations in schools can be highly context-dependent and convey different results.

Most studies on indoor air quality in schools have concentrated on the student population and its effects on student health and cognitive performance. In contrast, only a few have examined associations between teachers' health and the classroom's indoor environmental conditions (Brink et al., 2021; Lin et al., 2017, 2020). Teachers spend most of their workday in classrooms, constantly exposed to the indoor air pollutants in these spaces. These exposures may affect teachers' ability to teach through various health symptoms, which indirectly affects children's learning ability. This study focuses on teachers as the primary group of interest. The rationale behind this choice is that teachers are influenced by the school environment just as much as students, and they play a crucial role in shaping classroom environmental conditions. Even more, in elementary school classrooms, students often have to ask for teachers' permission to open or close a window or door. Hence, the indoor environmental conditions of classrooms tend to respond to the teachers' preferences instead of those of students (de Dear et al., 2020). In addition, in lower grades, students might be too young to understand questions related to air quality and health, and parents might be reluctant to provide their permission to participate in the study.

This chapter analyses indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations in three public schools in Concepción and SanPedro de La Paz in south-central Chile, along with a survey of teachers' perceptions, self-reported health concerns, and health symptoms in areas of energy poverty, and addresses the following questions (1) How is the air quality in Chilean schools during the winter? (2) How do teachers perceive their health and air quality in schools? (3) How does particulate matter concentrations affect teachers' self-reported health symptoms and concerns?

4.2.Methods

4.2.1. The schools

The study was conducted in three public schools in south-central Chile, in the neighboring cities of Concepción and San Pedro de la Paz. The cities are located at -36º 46' 22" latitude and -73º 03' 47" longitude, with an average height above sea level of 12 m (39.4 ft) and are geographically separated by the Biobio River (Figure 4-1). According to the Köppen Geiger classification, the cities have a Csb climate (Warm-summer Mediterranean climate). Their winter spans from May to August, where July is the coldest month, with an average temperature of 48.2°F (9ºC), and the rainiest month is June, with an

average rainfall of 145 mm (Climate-Data, n.d.). All schools are in urban residential areas with different immediate contexts. School CH-Z is a two-story building that faces a neighborhood park, school CH-I neighbors a small butte and school CH-G is adjacent to a major highway, with heavy traffic and cargo (Figure 4-2). All the schools are naturally ventilated and have operable windows.

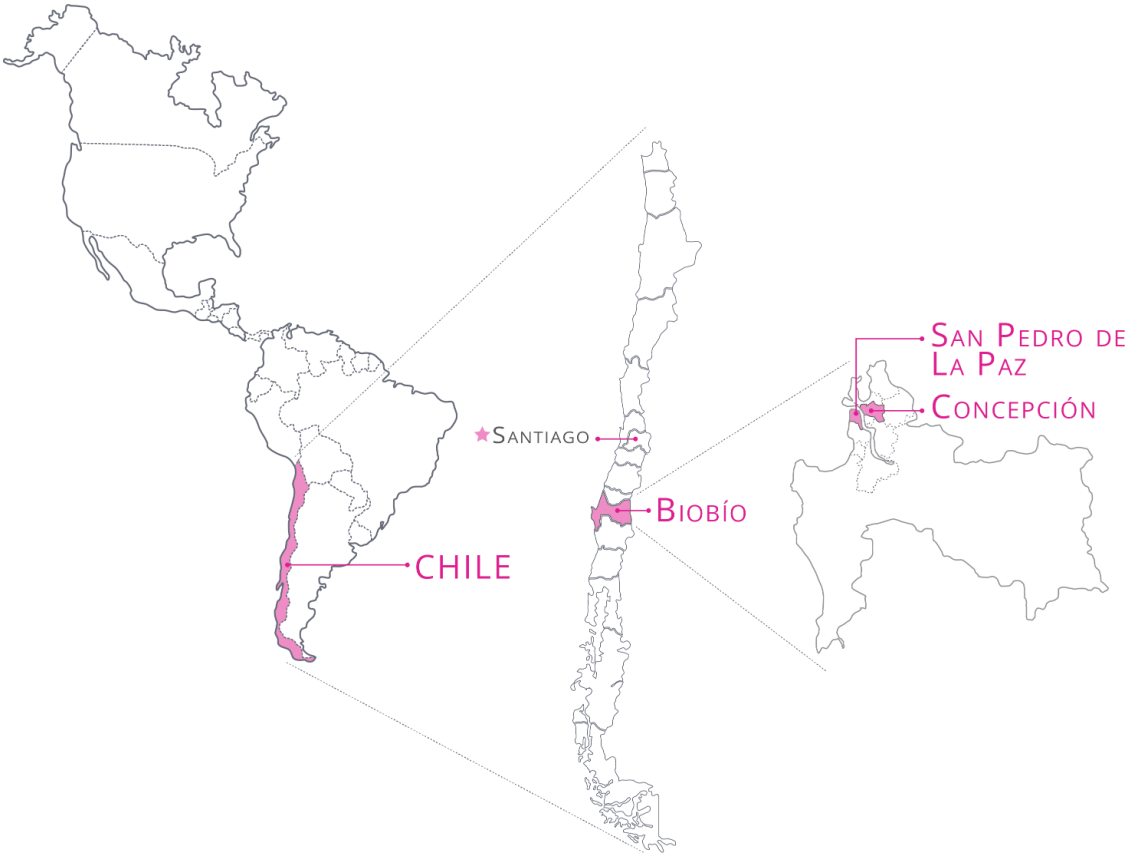


Figure 4-1 Location of Concepcion and San Pedro de La Paz



Figure 4-2 Schools and sensors' location.

4.2.2. Physical measurements

Two neighboring first and second-grade classrooms were selected in each school for the study (Figure 4-3). In elementary schools in Chile, the same teacher imparts most subjects. Teachers stayed in the classroom with the students most of the time, which helped ensure the equipment's safety and the reliability of teachers' perceptions of the classroom. Depending on the available space, the measuring station was placed in the back or front of the classroom to avoid interrupting classes and to prevent children from tampering with the equipment (Figure 4-4). Each station was placed from Monday through Friday during the winter of 2023 to gather data on a typical academic week (Table 4-1). Sensors were moved from school to school every week. Classrooms had normal occupancy in all schools during the measuring week, except for school CH-G, where there was a teacher strike on Wednesday and Thursday, so those days measurements were recorded without occupancy.



Figure 4-3 Examples of classrooms included in the study from each school

A Dylos DC1700-PM air quality monitor recorded indoor $PM_{2.5}$ and PM_{10} mass concentrations ($\mu g/m^3$) every minute. The sensor was located at 0.9 m (3 ft) in height to stay inside the breathable zone of the students and teachers when they were sitting down. Also, a Purple Air Zen sensor (counting efficiency 50% at 0.3µm & 98% at ≥0.5µm), was installed in an outdoor area of each school during the same week, recording outdoor $PM_{2.5}$ and PM_{10} concentration readings ($\mu g/m^3$) every 2 minutes. All data from indoor and outdoor sensors was cleaned and averaged at 10-minute intervals to make it comparable. Due to measurement errors, data from one classroom in school CH-Z and one in CH-G was removed from the

analysis. Measurements in the two classrooms in school CH-I were averaged to report and compare them with the results of the classrooms in the other schools.



Figure 4-4 Measuring station crates placed in the back of the classroom

Physical measurement data was analyzed in four different ways. First, statistical tests were conducted using R studio to understand the influence of the immediate context on the school's outdoor PM concentrations. Since the data was not normally distributed, differences between the schools were tested using non-parametric Kruskall-Wallis tests. The following pairwise comparisons were developed using the Dunn procedure, with *p*-values adjusted with the Bonferroni correction. Second, Kendall tau correlations were used to evaluate the association between outdoor air quality (AQ) and indoor air quality (IAQ) in each school. Third, to assess the indoor air quality of each school, the 24-hour average $PM_{2.5}$ and PM_{10} concentrations were compared with international and local standards. Finally, physical measurements were grouped into three 8-hour occupancy periods to assess daily differences in PM concentrations, which represented (1) normal occupancy (class) from 8 am to 3 pm, (2) evening/unoccupied (pm) from 3 pm to midnight, and (3) early morning/unoccupied (am) from midnight to 8 am.

Table 4-1 Classroom characteristics and physical measurements summary.

School	Dates	Floor	Area m^2 [ft^2]	Max. occupancy	Heating system	Equipment location	
						Indoor	Outdoor
CH-Z	07/17 to 07/21	2	46.5 [500.5]	34	Radiant fan in the back + gas heater (not working)	Front	Interior courtyard façade
CH-I	07/24 to 07/28	1	45.0 [484.4]	25	None	Back	Side façade to green space
		1	45.0 [484.4]	25		Back	
CH-G	07/31 to 08/04	1	37.2 [400.4]	32	Radiant fan in the front + gas heater next to the teacher	Back	Main façade adjacent to the highway

4.2.3. Surveys

An online questionnaire was distributed to teachers in all schools during the same week of the physical measurements. The questionnaire was based on the MM-040 questionnaire from the Örebro Model (Andersson, 1998) and adapted from the long-term thermal comfort assessment survey of the ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy (ASHRAE, 2023b) to fit the purpose of this study. In this paper, we only report the results of questions related to teachers' perceptions regarding long-term (last year) and short-term (last week) indoor and outdoor air quality, health concerns, and self-reported health symptoms in the last three months (Table 4-2). The sample of teachers in each school varied depending on the school's size and the teachers' availability at the time of the survey. A total of 78 responses were received from teachers in the three schools: 36 from school CH-Z, 16 from school CH-I, and 26 from school CH-G, with nine incompletes.

Table 4-2 Survey questions and measures.

Health	Question type	Measure
What do you think of the overall outdoor air quality surrounding the school in the last school year?	5-point acceptability scale	Outdoor air long-term acceptability
How frequently do you find the outdoor air surrounding the school is not acceptable?	5-point frequency scale	Outdoor air acceptability frequency
What do you think of the outdoor air quality surrounding the school in the last week?	5-point acceptability scale	Outdoor air short-term acceptability
What do you think of the indoor air quality of your classroom in the last week?	5-point acceptability scale	Indoor air short-term acceptability
For each of the following potential issues, please rate how much of a concern it is for you in the classroom where you teach.	Matrix - 4-point assessment scale	Health concerns
Have you ever had any of the following respiratory issues?	Matrix - Multiple choice	Previous respiratory health problems
Do you smoke?	Multiple choice	Previous respiratory health influence
During the last 3 months, have you had any of the following symptoms?	Matrix - Multiple choice	Health symptoms & frequency

4.3.Results

4.3.1. Indoor and outdoor air quality in Chilean classrooms

Upon visual examination of outdoor $PM_{2.5}$ and PM_{10} measurements, it was apparent that the data did not follow a normal distribution. Therefore, non-parametric Kruskall-Wallis tests were used to assess differences between the schools, which revealed significant differences in the distributions of $PM_{2.5}$ and PM_{10}. In addition, pairwise comparisons revealed that these differences occurred in all pairings, except for the pair between CH-I and CH-G, even when these two schools have different neighboring contexts (Figure 4-7 and Figure 4-8). In all schools indoor PM concentrations were higher than outdoor concentrations, as indoor/outdoor concentration ratios for $PM_{2.5}$ the schools were 1.3 for CH-G, 1.1 for CH-I, and 1.4 for CH-Z. For PM_{10} these were 1.7 for CH-G, 1.6 for CH-I, and 1.9 for CH-Z. In addition, when assessing the correlation between indoor and outdoor air quality, Kendall tau correlations showed that the strength and direction of association between indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations were positive and significant at the $p < 0.001$ level (Figure 4-5 and Figure 4-6) . Therefore, outdoor AQ had a substantial influence on classroom IAQ.

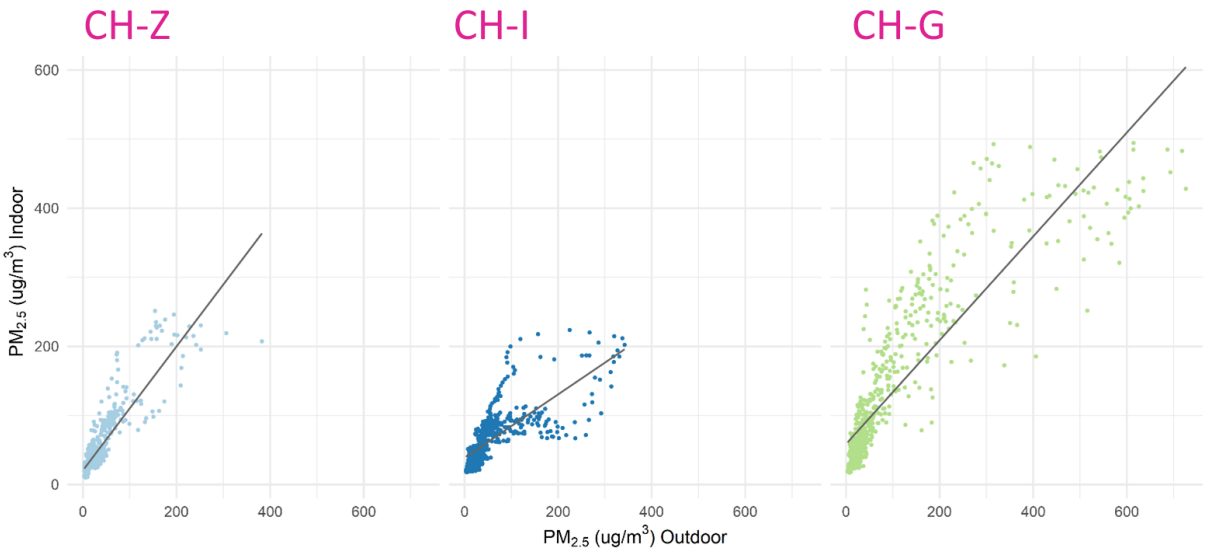


Figure 4-5 Indoor/outdoor $PM_{2.5}$concentration correlations in each school

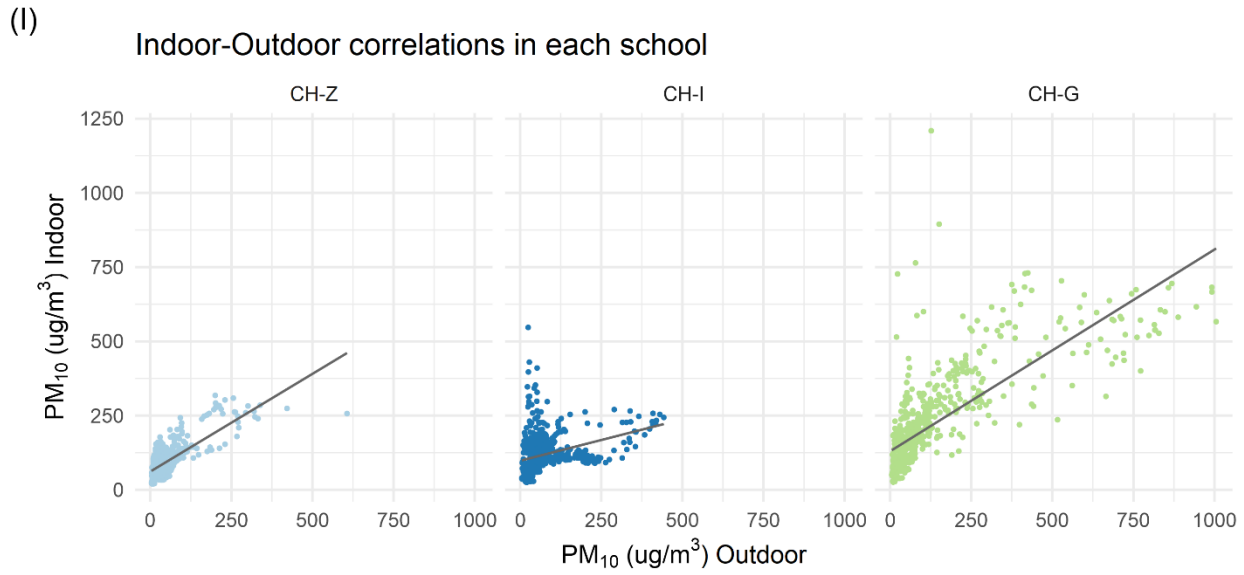


Figure 4-6 Indoor/outdoor PM_{10} concentration correlations in each school

Following these tests, 24-hour averages of indoor $PM_{2.5}$ and PM_{10} concentrations were compared with international and local air quality standards. The latest air quality guidelines (AQG) from the WHO recommended short-term 24-hour exposures to $PM_{2.5}$ at concentrations no larger than 15 µg/m^3 and 45 µg/m^3 for PM_{10}. In addition, the same document establishes interim targets for highly polluted places, with the least stringent being Interim Target 1, with limits of 75 µg/m^3 for $PM_{2.5}$ and 150 µg/m^3 for PM_{10} (WHO, 2021).On the other hand, the Chilean Ministry of the Environment defined the Primary Environmental Quality Standard for $PM_{2.5}$ and PM_{10} concentrations in the Decree 12 of 2011 and 2022. The regulation establishes the limits for 24-hour exposures of $PM_{2.5}$ as 50 µg/m^3 and 130 µg/m^3 for PM_{10} (Ministerio de Medio Ambiente, 2011, 2022). In addition, the Chilean regulations consider a state of environmental emergency when 24-hour mean PM concentrations are above 170 µg/m^3 for $PM_{2.5}$ and 330 µg/m^3 for PM_{10}.

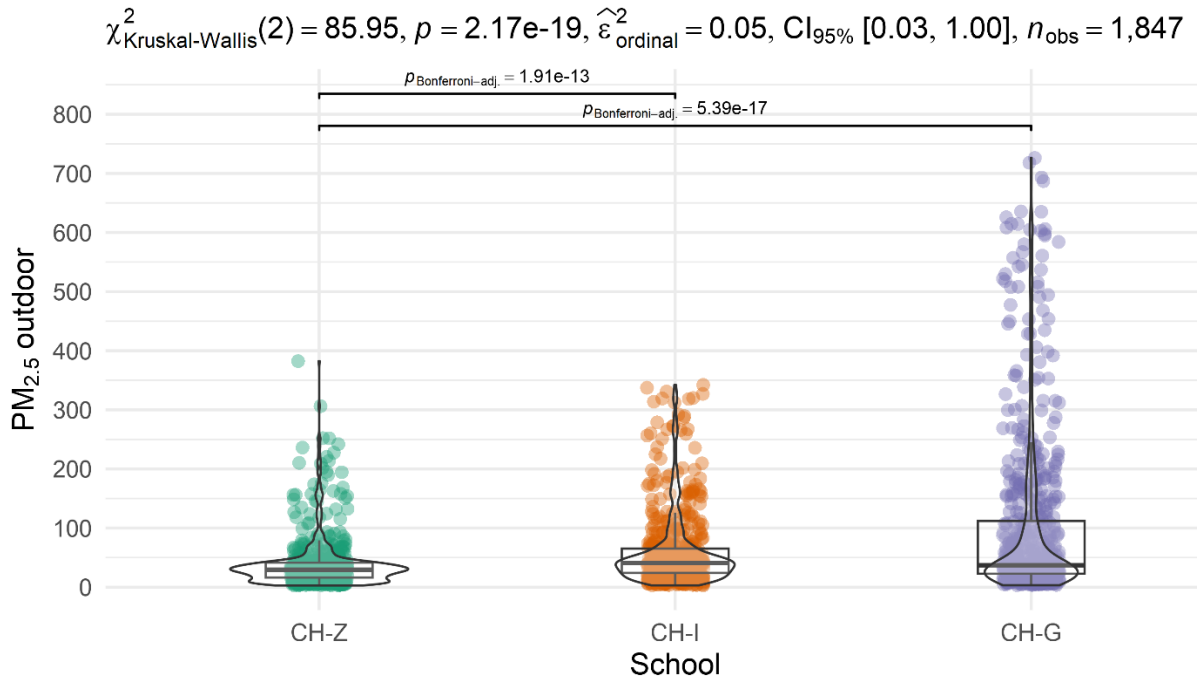


Figure 4-7 Differences in $PM_{2.5}$ outdoor concentrations for the three schools

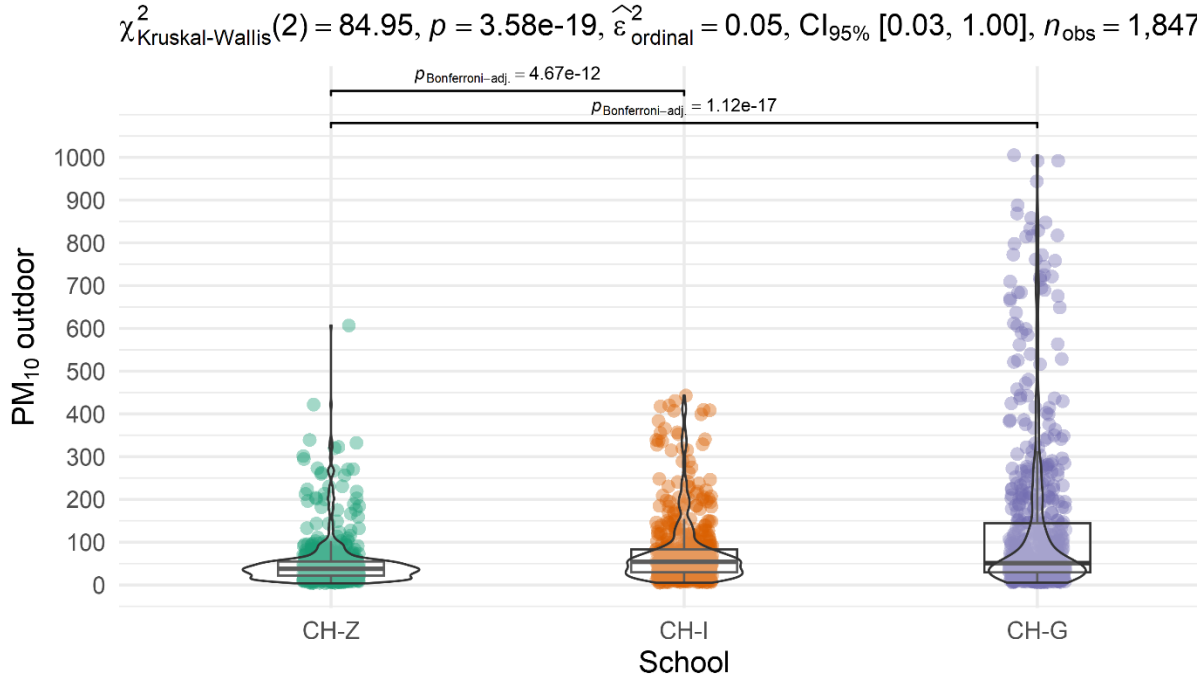


Figure 4-8 Differences in PM_{10} outdoor concentrations for the three schools

All schools exceeded the most stringent 24-hour AQG of the WHO for $PM_{2.5}$ and PM_{10}, both indoors and outdoors. Since the Chilean local regulations and the Interim Target 1 from the WHO are less strict than the AQG, the schools complied with these standards more often, but not every day (Figure 4-9 and Figure 4-10). Even more, the average concentrations of indoor $PM_{2.5}$ recorded in 2 days in school CH-G fell into the environmental emergency category of the Chilean regulations. Interestingly, the school was empty due to the teacher strike on one of those days, meaning that the high $PM_{2.5}$ concentrations were unrelated to any school activities.

When comparing different moments of the day, the average $PM_{2.5}$ concentrations in all schools were lower during class times (Table 4-3). In addition, in CH-I and CH-Z, the highest average $PM_{2.5}$ concentrations occurred during the evenings, while in CH-G this happened in the early hours of the day. Regarding PM_{10}, in CH-I and CH-Z, the lowest average concentrations occurred in the early morning, while for CH-G, this occurred during class time. The highest average PM_{10} concentrations occurred at different times in each school: in the early morning for CH-G, during class for CH-I, and in the evenings for CH-Z. Even with the occupancy groupings, all schools failed to comply with the WHO AQG while the school was in session. Additionally, CH-G failed to comply with the local regulations during class time, and the average concentration in the early morning fell into the environmental emergency category.

Table 4-3 Indoor and outdoor $PM_{2.5}$ and PM_{10} average concentrations in different occupancy periods

	Indoor $PM_{2.5}$				Outdoor $PM_{2.5}$			
School	am	class	pm	24-h	am	class	pm	24-h
CH-Z	49.3	38.4	82.3	55.8	27.1	24.2	68.7	39.3
CH-I	64.4	54.1	81	66.2	41.2	34.4	106.1	59.9
CH-G	178.8	76.7	155.8	134.3	119.4	37	149.1	100.8
	Indoor PM_{10}				Outdoor PM_{10}			
CH-Z	74.2	98.8	111.5	95	36.1	31.5	89.2	51.3
CH-I	82	144	128.9	119	54.7	43.8	130.9	75.6
CH-G	262.4	169.9	233.4	219.3	161.4	48.7	190.4	131.8

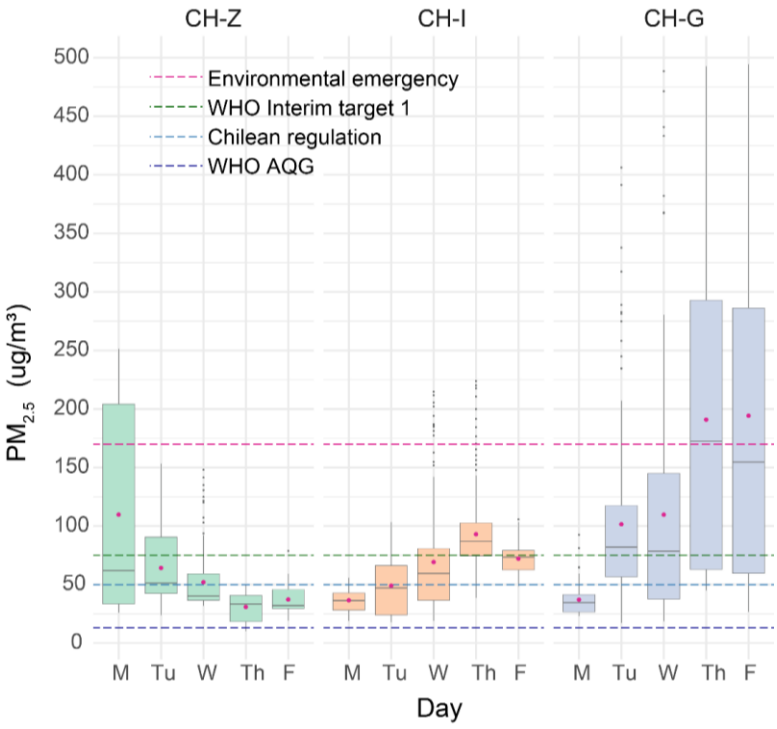


Figure 4-9 Daily distribution of indoor $PM_{2.5}$ measurements in comparison to local and international guidelines. Red dots represent averages.

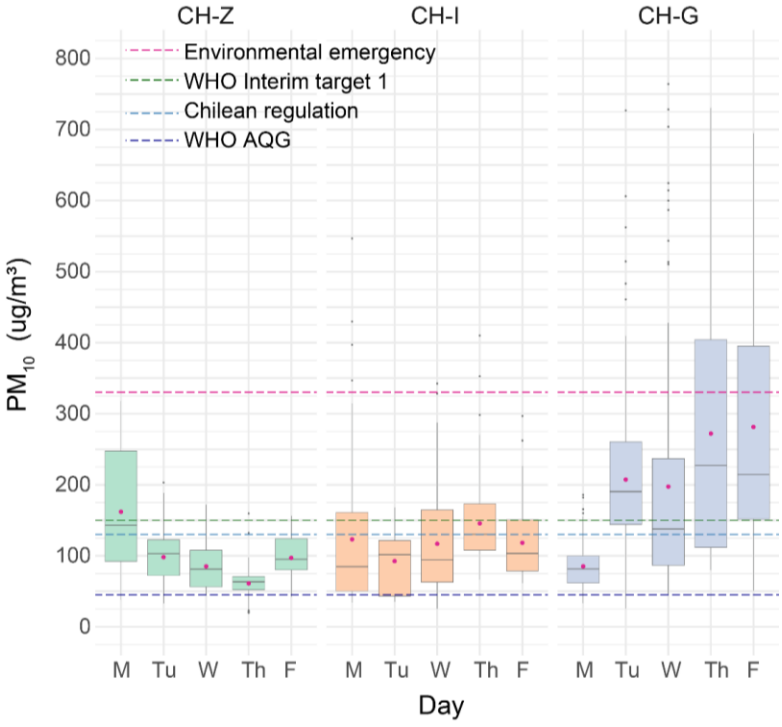


Figure 4-10 Daily distribution of indoor PM_{10} measurements in comparison to local and international guidelines. Red dots represent averages.

4.3.2. Teacher outdoor and indoor air quality perceptions

The first three survey questions inquired about outdoor air quality (AQ), and the fourth inquired about indoor air quality (IAQ) perceptions. Of all the surveyed teachers, 41.3% deemed outdoor AQ acceptable in the last year. Nonetheless, there were differences between the perceptions in each school. In school CH-G teachers had more negative perceptions, with 52.9% perceiving it as either bad or very bad, while in schools CH-I and CH-Z, this only occurred with 6.25% and 20% of teachers, respectively. On the other hand, in school CH-I, 62.5% of the teachers perceived AQ in the last year as good or very good, while this only occurred in 24% of CH-Z and 11.8% of CH-G teachers. Finally, 56% of teachers in school CH-Z, 31.25% in CH-I, and 35.3% in CH-G thought AQ was acceptable (Figure 4-11).

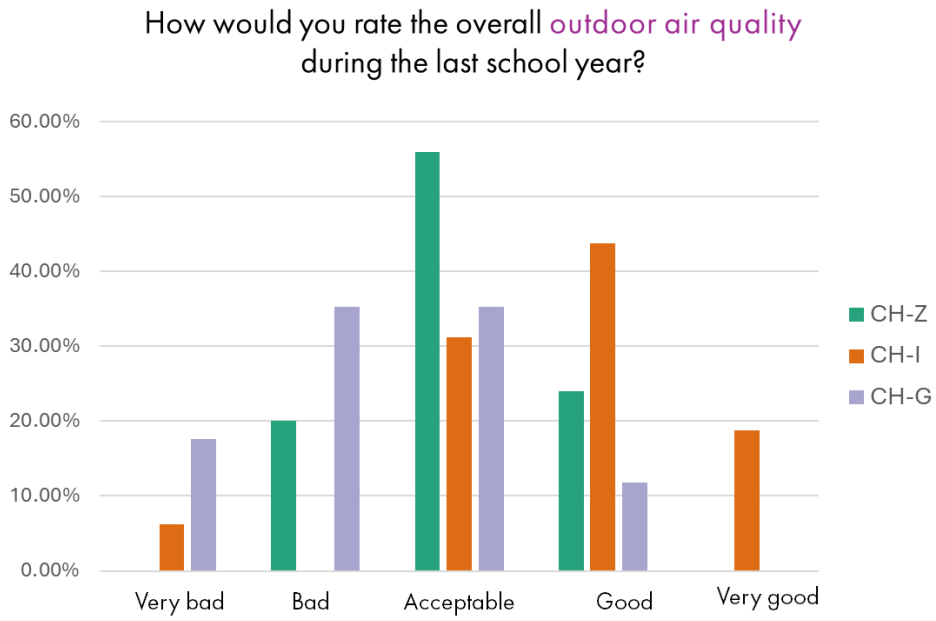


Figure 4-11 Teachers' perceptions of outdoor air quality in the last school year

A total of 37.3% of all teachers reported not finding AQ acceptable either once a month or during a specific period of the year. Nonetheless, following a similar pattern as the previous question, in school CH-G this occurred for 40% of teachers at least once a week. In comparison, in school CH-I, 50% of teachers never or rarely found AQ to be unacceptable. Finally, in CH-Z, 45.8% of teachers found AQ was not acceptable only occasionally (Figure 4-12).

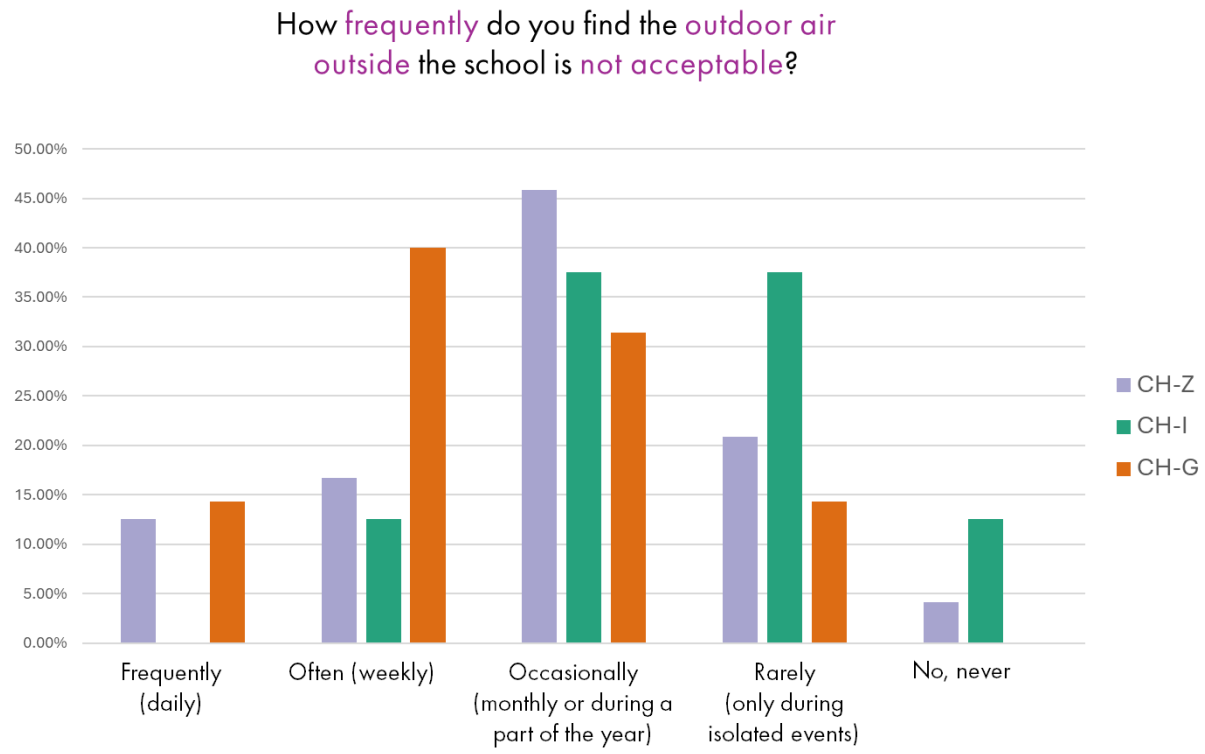


Figure 4-12 Frequency in which teachers didn't find outdoor air acceptable

Perceptions about AQ during the week of measurements rendered similar results as general AQ perceptions. Overall, 26.7% of teachers thought AQ was good or very good, 41.3% thought it was acceptable, and 32% thought it was bad. Teachers in school CH-G had the worst perceptions overall, as 52.9% stated AQ was bad during that week, while in schools CH-Z and CH-I, this only occurred with 20% and 6.25% of respondents, respectively. On the contrary, 50% of teachers in school CH-I evaluated AQ in the last week as good or very good, while this only happened with 28% and 14.7% of respondents in schools CH-Z and CH-G. Finally, 52% in CH-Z, 43.7% in CH-I, and 32.35% in CH-G thought AQ was acceptable (Figure 4-13).



Figure 4-13 Teachers' outdoor air perceptions during the measurement week

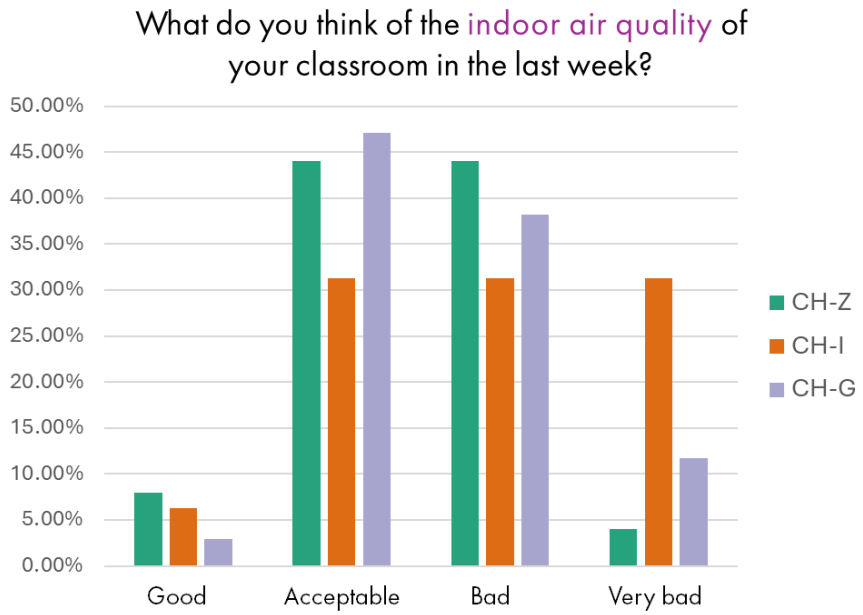


Figure 4-14 Teachers indoor air quality perceptions during the measurement week

Regarding indoor air quality (IAQ) in the classroom, 42.7% of all teachers considered it acceptable, 38.7% said it was bad, 13.3% very bad, and only 5.3% thought it was good. In this case, teacher perceptions in all schools were more negative than with outdoor air quality. Nearly half the teachers in

each school considered IAQ in the classrooms bad or very bad. This perception was distributed among the schools like this: 62.5% in CH-I, 50% in CH-G, and 48% in CH-Z. Nonetheless, a large portion of respondents thought the IAQ was acceptable: 44% in CH-Z, 31.25% in CH-I, and 47.06% in CH-G, while only a small percentage considered the IAQ good: 8% for CH-Z, 6.25% for CH-I, and 5.33% for CH-G (Figure 4-14).

4.3.3. Teacher health concerns and symptoms

The main health concerns among teachers were extreme cold waves or cold snaps, as 69% of all respondents considered them a big problem, with similar trends for all schools. Similarly, respiratory viruses were the second health hazard that concerned teachers the most in all schools (48.6%). Also, 21% of all teachers listed heat waves as a big problem, making it the third most frequent response. Interestingly, most of these responses came from school CH-I (40%), while in schools CH-G and CH-Z, heat waves were a problem only for 18.8% and 12.5% of respondents. In addition, heat waves were not a problem for 34.4% of teachers in CH-G and 37.5% in CHZ, while this only occurred for 20% in school CH-I. Therefore, the origin of this concern might be related to a unique characteristic of school CH-I.

Other IAQ problems such as mold or mites, pollen, allergies, outdoor air pollution, or irritant off gassing from paint or other materials were only big problems for under 20% of all respondents. Interestingly, only 13% of respondents considered outdoor air pollution a big problem. Moreover, 34.78% and 46.67% of teachers in schools CH-Z and CH-I did not consider it a problem at all (Figure 4-15). In addition, 62% of respondents in all schools had never had asthma, but 24% had had it, including the last year. This accounted for 25% of respondents in schools CH-Z and CH-G, while in CH-G, it was only 20%. Regarding hay fever, 54.3% of respondents reported having it during the last year (65.3% in CH-G, 43% in CH-I, and 45.8% in CH-Z). In addition, 60% of respondents reported never having dermatitis, and only 30% reported suffering it during the last year. Finally, 18.3% of teachers reported smoking often, 18.31% smoking occasionally, and 12.68% reported that they used to smoke but did not do it anymore.

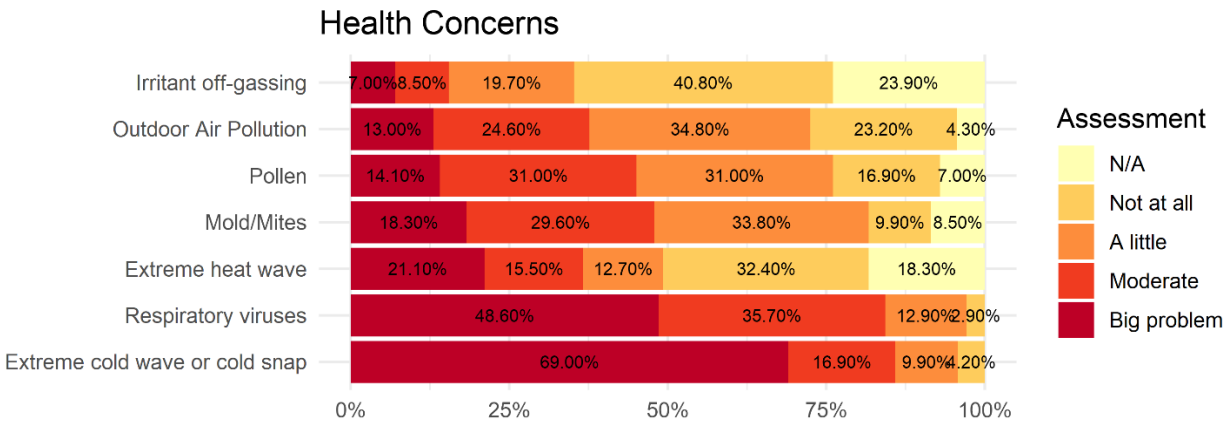


Figure 4-15 Teacher's health concerns in the last three months.

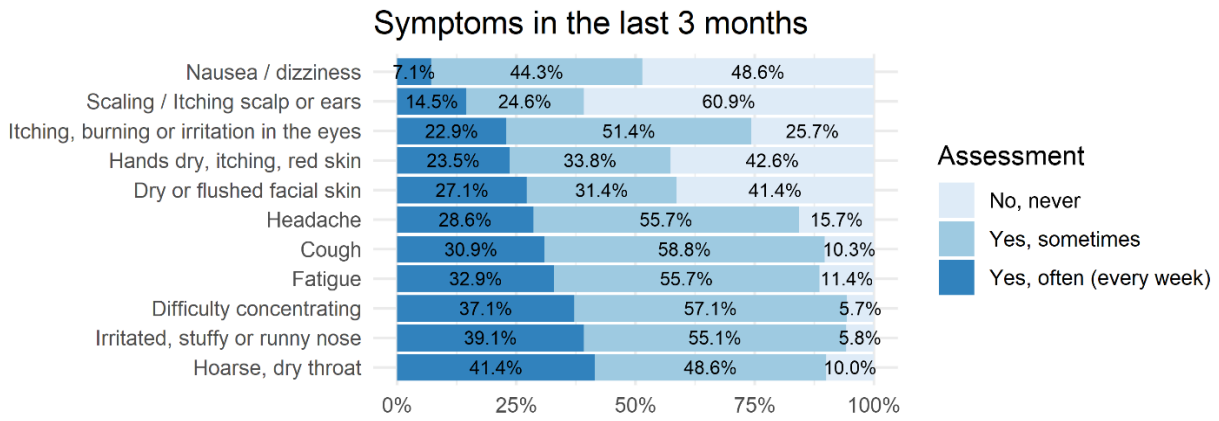


Figure 4-16 Teacher's self-reported health symptoms in the last three months.

The most prevailing and frequent health symptoms among teachers in all schools were hoarse or dry throat (41.4%), closely followed by a stuffy, irritated, or runny nose (39.1%), and difficulty concentrating (37.1%), with all schools following similar patterns. On the other hand, the least self-reported symptoms in the last three months were nausea or dizziness (7.1%), scaling or itching of the scalp or ears (14.5%), and itching, burning, or irritation of the eyes (22.9%) (Figure 4-16).

4.4. Discussion

The location of the schools proved to have an influence on daily PM measurements. School CH-G had the highest $PM_{2.5}$ and PM_{10} concentrations, likely due to its location near a major highway. Nonetheless, the lack of significant differences between the distribution of PM concentrations in school CH-I and CH-G revealed that other sources of pollution are ubiquitous in both cases. In the case of Concepción and San Pedro de la Paz, this can be explained by the prevalence of firewood stoves in both cities, which generates PM pollution during the colder moments of the day all over the city.

Indoor and outdoor air quality were significantly correlated, indicating that outdoor PM has a major influence on IAQ. All the schools included in this study are naturally ventilated, have leaky envelopes, and have old windows that sometimes do not close properly, making indoor and outdoor conditions highly correlated. What is problematic though, is that outdoor air conditions surpassed the WHO guidelines and, on occasion, reached environmental emergency conditions. Public schools in these cities do not have on-site tools to monitor indoor and outdoor air quality. Therefore, they must rely on the few governmental stations available, which might not account for localized conditions. Consequently, schools cannot keep records of their air quality and do not have the tools to take any action towards improving it.

Data analysis using 8-hour periods allowed us to address differences in PM concentrations at different moments of the day. Average $PM_{2.5}$ and PM_{10} concentrations were higher indoors than outdoors during class time. Teachers kept the door, and most windows closed to preserve the warmth inside and avoid noise coming from outside, which can cause the resuspension of PM inside the classroom and a lack of air renovation during the day. In addition, some classrooms used a radiant fan for heating for a couple of hours in the morning, which might increase PM resuspension and decrease IAQ.

Class periods represented the lowest average $PM_{2.5}$ concentrations in every school. In contrast, evening periods had the highest $PM_{2.5}$ concentrations in CH-I and CH-Z, corresponding with the moments when residential areas turn on the woodstoves for heating. In contrast, in school CH-G, the highest $PM_{2.5}$ average concentrations occurred in the early morning, possibly due to early morning traffic on the highway. In addition, the average $PM_{2.5}$ concentration in CH-G in the evenings was still higher than that of the other two schools, and reached pre-emergency levels according to Chilean regulations (Ministerio

de Medio Ambiente, 2011, 2022). These results show how PM impacts come mainly from neighboring sources, including the highway and the residential areas adjacent to the schools. The high evening PM records correspond with issues related to city-wide energy poverty. Even when occupants' exposure to $PM_{2.5}$ is lower during regular class times, they are likely still exposed to high pollution levels when not at school.

Teachers' general outdoor AQ perceptions showed differences between schools. While over half the teachers in school CH-G perceived it as mostly negative in the last year and last week, for school CH-I, general perceptions were mainly positive. However, the physical measurements presented a different story, showing that while the AQ in CH-G was worse than CH-I, it was not ideal either in CH-I, given the overarching impact of wood burning in the area, especially during the evenings. In this case, these perceptions might be related to the school having a large green area and neighboring a butte instead of a major highway. Teachers might associate seeing greenery next to the school with perceiving good AQ.

Indoor air quality perceptions proved to be more negative than outdoor AQ perceptions in all schools. In this case, responses in all schools rendered very similar results despite the differences in PM concentrations evidenced by physical measurements. Even in CH-Z, where the indoor PM concentrations were lower compared with the other two schools, almost half the teachers considered the air quality as bad or very bad. In this case, teachers' perceptions might be coming from a different origin. Since the project was developed during the winter, the most concerning health hazards reported were cold snaps and respiratory viruses. Therefore, teachers might have been associating IAQ with cold indoor air temperatures in the classroom and viruses due to crowdedness, instead of PM concentrations.

General health questions and self-reported health symptoms had similar response trends in all schools. The most frequently reported symptoms were related to teaching, such as hoarse and dry throat, which corresponds with previous findings (Brink et al., 2021). Respiratory symptoms were also reported as being frequent, which might be related to the overall poor air quality in the city, low relative humidity, and low temperatures during the winter. Since the study only covered the teacher's time at school, it was

not possible to assess other influences they were exposed to during other periods, which might be the most critical for PM exposure times, as shown by the physical measurements.

4.5. Conclusions

The study analyzed PM pollution concentrations on air quality in school facilities in Concepcion and San Pedro de La Paz. The results showed high indoor and outdoor PM concentrations, evidencing the prevalence of PM air pollution in the area. The use of wood stoves for heating in residential areas neighboring the schools was the main source of PM pollution, as concentrations spiked during the evenings and nights. These results highlight the urgency to improve current energy sources. The current Plan for Prevention and Atmospheric Decontamination (PPDA) of the Concepcion Metropolitan region, includes actions such as improving the type of wood for heating, upgrading heating devices, and enhancing the energy efficiency of dwellings (Ministerio del Medio Ambiente, 2019). Despite the formulation of the plan years before the development of this research, our results show that the efficacy of its execution is not yielding visible results yet. Studies like this one provide further proof to a call for action on this matter to bring this forward to the political scene.

Future research could further investigate low-cost sustainable technologies and strategies suitable to the local context to replace the current wood burning stoves, as well as affordable ways to increase the energy efficiency of the existing residential building stock. For instance, studies have shown that for low and middle income households, retrofitting traditional woodstoves can improve their performance and reduce emissions (Carvalho et al., 2018). Also, modern woodstoves or pellet stoves have been found to emit lower quantities of particulate material than traditional woodstoves (Bäfver et al., 2011), when other heating sources are not economically feasible. In addition, future studies could investigate the efficiency of interventions using low-cost technologies, like Corsi filters to clean the air and improve indoor air conditions.

The research also showed that teachers' perceptions of air quality did not always correspond with the physical measurements. A high percentage of the sample did not consider outdoor air pollution a significant health hazard. Teachers are accustomed to living in the same polluted conditions every winter,

so they may not perceive it as a risk. As the health effects of air pollution occur only after chronic long-time exposure, people might not consider it an imminent threat. Nonetheless, Chile suffers approximately 4000 premature deaths every year due to air pollution (UNEP, 2017), and the prevalence of energy poverty makes it an even more pressing situation.

These results provide a general idea of the indoor and outdoor air quality conditions in the south-central region of Chile and unveil the existing disconnect between air quality conditions and air quality perceptions. The study was limited by only exploring teacher's exposures during their time at school and a short measuring period, so it was not possible to define a clear relationship between PM exposures and self-reported health symptoms. Nonetheless, since high PM pollution occurs all over the city, teachers are likely exposed to high PM concentrations outside school hours. Future research using mobile sensors could shed more light on the effects of daily PM exposures on personal health.

4.6.Bridge

This chapter presented a case study on air quality and teacher health in the context of energy poverty in Chile, focusing on measurements of particulate matter pollution in three schools in the Gran Concepción metropolitan region. While this and the previous chapter were more focused on quantitative results and developed a case study each, the following two chapters are two parts of the California case study. Chapter 5 covers the qualitative analysis of the interviews with teachers and facility managers, and Chapter 6 combines the qualitative analysis with the quantitative results of the physical measurements to provide a holistic idea of the multiple influences that shape indoor environmental conditions in schools.

5. The Construction of Thermal Comfort and Indoor Air Quality in Southern California Schools

The case study described in this chapter was conceptualized, developed, written and reviewed by Maria C. Coronado. The manuscript was developed for future publication.

5.1. Introduction

Indoor environmental quality in school facilities is crucial for teaching and learning processes. In particular, adequate ventilation has been associated with better student performance and health (Fisk, 2017; Wargocki & Wyon, 2017), especially regarding concentration and speed in performing various academic tasks (Bakó-Biró et al., 2012; Haverinen-Shaughnessy & Shaughnessy, 2015). Similarly, studies have found that even slight increases in temperature can affect students' school performance (Wargocki & Wyon, 2007b, 2013, 2017).

Studies in this area often concentrate on the environmental conditions of classrooms along with children's perceptions. Nonetheless, multiple stakeholders and other actors[1] directly or indirectly shape the classroom environment. For instance, teachers are often in control of the classroom, and dictate what changes are made to the environment, for example, opening or closing windows or doors (de Dear et al., 2020). These adaptations depend on the type of ventilation system. In mechanically ventilated spaces, they might be limited to modifying the thermostat, or to personal adaptations like adding or removing clothes. However, previous research has shown that similar behaviors occur in classrooms with different ventilation modes, especially in elementary schools (Singh et al., 2019).

Aside from teachers, there are other stakeholders that play a role in keeping adequate indoor environmental conditions in classrooms. For instance, facility maintenance managers oversee school facilities' physical state and environmental control systems, indirectly influencing the environmental

[1] In this case the word actor follows the definition given in Actor-Network-Theory (ANT), where human and non-human entities (objects and environments) can allow, afford, encourage, suggest, or influence actions, but do not determine them (Yaneva, 2009, 2022).

conditions of classrooms. In addition, federal and local regulations, technical standards, budget constraints, and the characteristics of each school district, among other elements dictate these conditions and help regulate the indoor environmental quality of classrooms. This case study uses a grounded theory approach to investigate the ways in which the relationships between three key stakeholders/actors: maintenance managers, teachers, and the classroom's physical environment co-construct the indoor air and thermal conditions in Southern California classrooms.

5.2.Methodology

This research was conducted through semi-structured interviews with 10 teachers and four maintenance managers in three school districts in Southern California during the summer of 2023. The participating school districts are located on Coastal, Inland, and Desert areas, and each district provides maintenance services to a different number of schools. The Desert district oversees 27 schools, while the Inland and Coastal ones manage 72 and 84, respectively. The study included teachers from five different elementary schools. In four of them, teachers were selected through purposeful sampling, selecting one teacher currently teaching in a portable classroom and one teaching in a permanent classroom. The remaining school was brand new and had no portable classrooms, so the two interviews corresponded to teachers in new classrooms.

Interviews with managers and teachers were specific to their roles at the school. Maintenance managers' interviews lasted 40 to 50 minutes and included 25 open-ended questions that covered 6 broad areas: (1) Experience, (2) Budget and prioritization, (3) Diagnosis and documentation, (4) Maintenance practices, (5) Interactions with occupants, and (6) Vision and desires. Teacher interviews lasted from 20 to 30 minutes and included 12 questions on 5 areas: (1) Experience, (2) Maintenance knowledge, (3) Comfort perceptions, (3) Environmental controls, and (4) Vision and desires. The interviews were conducted on-site at each school or district office. In addition, an observation log and photographs of the classrooms were taken during the fieldwork to correlate teachers' and managers testimonies with researcher observations (Figure 5-1).

All interviews were transcribed and coded using HyperResearch 4.5.6. The codes were analyzed and grouped into themes. Then, using code frequency analysis, a series of themes was extracted to create a narrative account exploring the construction of thermal comfort and indoor air quality in Southern California schools.



Figure 5-1 Images of a sample of classrooms of the participating teachers. (A) Older classroom in the Coastal SD. (B) New classroom in the Desert SD. (C) Retrofitted classroom in the Coastal SD. (D) Portable classroom in the Inland SD.

5.3.Findings and Discussion

The interviews revealed the inner workings of the relationships between teachers, maintenance managers, and the classrooms' physical environment. Each relationship has its own nuances, and they work together to co-construct the indoor air and thermal conditions of classrooms. The following sections present each relationship, its characteristics, and how the interactions between these stakeholders/actors work together to shape the indoor environmental quality in the case study classrooms.

5.3.1. Teachers and Maintenance Managers

5.3.1.1. Effective communication

School districts have multiple mechanisms to monitor the performance of school facilities and keep track of their maintenance needs. All districts have a work order system to manage regular maintenance, which is operated by the custodian or the front office's secretary at each school depending on the district, to communicate maintenance needs to district managers. Therefore, to request maintenance services from managers, teachers must email the point of contact person in their school, creating an indirect link between what happens in the classroom environment, and maintenance services. Besides this mechanism, managers carry out inspection walks with school administrators when required, which helps them keep track of the maintenance needs of every site, without directly communicating with the teachers. However, this relationship is nuanced by how school occupants and managers perceive each other:

"I would say it's probably 50/50, there are site administrators and teachers that really appreciate it, and, and know what we do… But then the other half doesn't care. We're, basically a necessary evil."
(Maintenance manager, Desert district)

Despite the transparent nature of the system, it is not always effective. Maintenance or repair needs are often not promptly reported to the district, fall under the wrong priority level, or are not attended in time due to district's limited capacity to respond simultaneously to multiple schools. There are many reasons why this could occur, but among the most pressing are time and staffing limitations. In the Desert district for example, custodians are the initial responders to maintenance needs, but they are often on a tight schedule and occupied with cleaning duties, so they may not always be aware of all facility issues.

Nonetheless, proactive management practices can help improve communication between districts and schools. In the Inland district, for example, the maintenance manager talked about encouraging principals and secretaries to contact him directly when faced with a high priority emergency, highlighting the importance of communication:

"I want to hear those, and I don't call them complaints, they are opportunities for us to succeed. I want to know about it, and I tell all the sites: you put a work order in the system for an HVAC unit. Please, the next thing you need to do is call our office because we completed 45000 work orders last year. So, if you're just putting it in the work order system, and it comes in medium priority, it's in with every other medium priority work order that came in that day. But we may be working on two days ago's work order. So, we don't know. And so, I've always asked my site administrators, after you put it in a work order system, give us a call… And I also provide customer service. I pick up the phone and then I call the site, and I tell them this is what I've got in motion for them, because I had a Superintendent tell me one time: information is like oxygen" (Maintenance manager, Inland district)

Similarly, in the Coastal district, the maintenance manager noted that through the ongoing collaboration with schools, they had developed strong relationships and an institutional understanding of the district. This enabled them to efficiently handle emergencies by knowing who to contact in each school and vice versa. However, the flipside was that whenever there was turnover among school administrators or point of contact personnel, communication became challenging as the chain of information was disrupted. Therefore, besides the work order system that mediates maintenance services, direct communication between managers and schools plays an essential role in maintaining adequate environmental conditions in classrooms.

5.3.1.2. Effective response

Teachers' level of information, personal experiences and awareness of how processes work help build confidence in maintenance practices to create adequate environmental conditions in classrooms. All the teachers who participated in the interviews were aware of the work order process but had different experiences with maintenance. Teachers who had had frequent or long-held negative experiences with the environmental controls of their classroom showed distrust towards the maintenance practices of the district. For instance, one of the teachers who lived a long-lasting negative experience at the time of the interview exposed her frustration like this:

"The AC hasn't worked all year. It stopped working last September, and no, they tried. They came out a few times in September, and then, nothing. No one came back. And so, this year in summer, I called, texted, emailed the principal and I said: The year is starting again. Can somebody please try and come out and fix it? so since August, the end of August, they've been trying to fix it, so I'm thankful today I came back, and it was working." (Teacher I, Coastal district)

In other cases, teachers who had not had negative personal experiences became wary of the schools' building systems because of the building age and insufficient information about their condition:

"It's a very old school, and so I'm not sure how often, you know, the filters are changed over, I'm not sure how often the air conditioner has been checked in and all of that, because it is a very, very old school. So maybe that's all mental. Maybe I'm thinking, oh, you know, something's wrong with everything." (Teacher A, Desert district)

In contrast, teachers who had positive experiences with maintenance and were knowledgeable of regular maintenance practices in the classroom showed positive emotions when talking about the maintenance practices of the district:

"It's very efficient. My AC went out, the AC went out one day in a few classrooms, and they had it fixed within a couple of hours […] usually when it goes out, they're pretty quick to come fix it. And then if it's something not immediate, not urgent, then we just fill out an online form and then it goes to the district office, and they usually come and fix it, usually within a couple of days. But they do have regular maintenance. The maintenance operations come in a couple of times; they have scheduled days when they come in. And so, you'll fill out any kind of repair that you need before they come in, and then they have a big crew that comes out to the school, and they do all the repairs that day." (Teacher E, Inland district)

In mechanically ventilated schools, the responsibility of maintaining classrooms' thermal and ventilation conditions largely falls in the hands of managers who oversee the building systems. However, facility maintenance highly depends on the process of reporting and responding to maintenance complaints. Therefore, teacher awareness of the process, the proper working of the chain of communication, how the

district informs schools about its maintenance capacity, and how effective it is to program and deliver maintenance services, are all key parts of the process of creating adequate indoor environmental conditions for learning.

5.3.2. Teachers and Classrooms

5.3.2.1. Environmental adaptations

Adapting to the summer heat to maintain proper hygrothermal conditions was the most prevalent topic in the interviews. In the classrooms included in this research thermal adaptations occur through three mechanisms: a) building environmental controls, b) personal adaptations, and c) additional portable environmental controls.

Building environmental controls

In Southern California, teachers' air conditioning operation and window/door opening capabilities in classrooms vary among districts. In the three districts, teachers have limited control over the thermostat. While all districts have slightly different temperature control ranges, they only allow teachers to go up or down 2 degrees, with setpoints of 72°F in the inland district, 74°F in the coastal, and 76 °F in the Desert district for cooling conditions. These temperatures represent a point of friction between maintenance management and teachers, as heat is at the center of maintenance complaints during the summer. These thermostat setpoints result from a negotiation between energy efficiency goals, existing policies, teachers' thermal comfort, and internal politics:

"We were having rolling power outages here in California. The Power Company of Southern California, Edison, recommended that everybody went to 68 for heating, and 78 cooling. So, we as a district did that, and we took control away at the school level and controlled it from the energy management system. Since then, we've taken it down to 76 from 78, and we actually have more complaints at 76 than we did at 78. Teachers' union. They wanted control of their thermostats back, and we negotiated and said no, we're not going to give you control back, but we'll give you 76. So that was the compromise." (Maintenance manager, Desert district)

These are not easy negotiations, as not all teachers agree with these policies, arguing that these temperatures are not enough to cover the thermal comfort needs of their students:

"Now that now that. At 72, it gets warm still, with 35 bodies in the summer. In September, or over the summer, it gets, it gets hot and the kids will ask me turn the AC on. Like honey. It's as far as it'll go cause now the district sets it at 72. And I think it's, personally, I think it's ridiculous that it's set at 72 for 35 students." (Teacher J, Coastal district)

In contrast, other teachers expressed that they saw value in having the temperatures in their classrooms managed from the districts:

"You know, I will say one of the things I noticed since we went to the more controlled environmental controls, I don't have to adjust the temperature quite as much." (Teacher H, Coastal district)

In the summer, temperatures in these districts can go above 100 ºF, so all the schools that participated in this research worked with air conditioning (AC). Most teachers were comfortable with the thermal performance of their classrooms as long as the AC was working properly, because without AC they have very limited additional adaptive opportunities. For instance, in the Inland and Desert districts, policies aimed at improving energy efficiency eliminated operable windows in new classrooms. Similarly, in the Coastal district, retrofitted classrooms only have one small operable window available. Portable classrooms in all districts on the other hand, still preserve operable windows for ventilation.

For most teachers, concerns about overheating classrooms came from anecdotes from experiences in previous classrooms and social media posts reporting very high indoor temperatures, most of which came from schools without AC.

"And it's very difficult like some of these teachers are like, how am I supposed to get these kids to learn? It's 98° in here. Like, it's just the social media, on any hot day heat wave day, it's just flooded with pictures of teachers' thermostats. And like the temperature at 95 and above which Is… I can't. I can't imagine I can't imagine…" (Teacher H, Coastal district)

In contrast, most teachers had positive personal experiences with their own classroom environment and schools' heat response protocols. They explained how during extreme heat events, when a classroom's AC malfunctioned, classes were relocated to the library or another classroom while the issue was resolved, ensuring minimal disruption to learning.

Teachers with available windows in their classrooms rarely opened them during the school year. They mentioned they used to open them as part of the COVID pandemic protocols, but since that wasn't mandatory anymore, they stopped doing it regularly, arguing reasons ranging from to teaching practices, views, and lighting preferences. They opted to keep windows and blinds closed to reduce glare on their whiteboards, avoid disruptions when using a projector, showcase student work or block the view to avoid distractions, particularly for young children (Figure 5-2). Interestingly, the latter contradicts previous research indicating that views improve student performance and psychological well-being (Browning & Rigolon, 2019; Li & Sullivan, 2016). Only one teacher mentioned not opening the window to avoid straining the air conditioning, and another stated that keeping the blinds down helped prevent overheating during the summer. This shows that window and blind use are triggered by multiple ideas besides heat exposure. Furthermore, the preference to avoid operable windows also stems from perceptions of safety. In a classroom with only one small high window, the teacher stated:

"It would be nice to have some views, but honestly, it's in this neighborhood. It's safer not to have too many windows." (Teacher F, Inland district)

However, in classrooms where all windows were fixed, especially in the Desert district, teachers expressed their desire to be able to open the classroom windows during the shoulder seasons. While they admitted that opening windows would conflict with using the air conditioning during the summer and winter, they saw value in being able to have cross ventilation using windows and doors when the weather was milder. As a couple teachers teacher put it:

"It would be nice if we could open windows, just to get some natural ventilation in here. You know, even if it's just like a vent, you know, window to get some, to get some natural air in here." (Teacher D, Desert district)

"I mean a window would be nice. A window that we can open, even these that are kind of up high, and if we can open those and just have that [ventilation], would be ideal, I would love that." (Teacher A, Desert district)

In contrast, opening doors was a common adaptation to control the temperature in all districts, which was a point of tension between managers and teachers. Maintenance managers stated that they constantly received calls having to do with teachers leaving doors open for too long, not allowing the AC to work properly. A solution to this issue was implemented in the Desert district, where they installed sensors to automatically turn off the AC after 15 minutes of door opening, forcing teachers to close the door:

"We did put on all the doors a switch that if the door is open for a certain amount of time, say 15 minutes, we shut it down, the air conditioning, or set it way, way high, higher, and that has helped all the open doors because people will prop their doors open no matter what temperature it is. And then we get a call that it was too hot in the room. So, the door switches have been very effective to... They have to close it and maybe keep it closed for like 5 minutes, and then the air conditioning turns back on. The teachers don't like it, but they learned to accept that one. So, I did close a lot of the doors." (Maintenance manager, Desert district)

This strategy allowed the district to maintain energy efficiency, and inadvertently provided teachers with a way to control the temperature. Teachers said they used this system to turn off the AC when children felt too cold inside, and regulate the temperature inside the classroom especially towards the end of summer:

"I tell the kids if you're cold, I'll open the door for a little bit, but then I have to remember to shut the door because then it will get stuffy, cause the air shuts off." (Teacher C, Desert district)

This highlights the importance of providing some degree of control for comfort, without compromising energy efficiency. Nonetheless, teachers' decision to open the door was influenced by the classroom's immediate context (e.g. noise, mosquitoes) and schools' safety and security protocols. Therefore, in some schools, teachers would refrain from opening doors completely to avoid any of these issues:

"There's protocol for safety issues that we have to maintain our doors closed and locked at all times. And so, it's very rare that we're allowed to have our doors open even when it's nice out and the breeze is, you know. It just depends. But right now, our protocol is to maintain all doors and windows closed and locked during school hours for safety reasons." (Teacher A, Desert district)

Air movement is an important modifier of thermal comfort. In this study, ceiling fans were only present in one of the classrooms, but the teacher appreciated them and kept them constantly running for air circulation (Figure 5-3). Something similar occurred in a portable classroom, where the teacher stated that they preferred turning on the AC fan for moving air inside the classroom instead of opening a window, during periods when no AC was needed:

I can manually turn on the fan, which I'll use in an instance of like, the temperature is fine, but I just need like air to circulate in the classroom. And I guess I do that rather than opening a window. And that's about it, I mean, other than that, I don't really touch it. (Teacher G, Coastal district)

Both teachers and managers have different degrees of influence over the classroom's built-in environmental control system and devices. While their availability is influenced by policies, practices and protocols on a higher level; on a ground level their use has to do with teachers' personal preferences and ideas about comfort, safety, security, teaching and learning, among others, which makes the environment of each classroom slightly different.



Figure 5-2 Student work displayed on non-operable windows below new blinds.



Figure 5-3 Fan constantly running inside the classroom while the teacher is in the classroom.

Personal adaptations

Adjusting clothing is the primary personal adaptation possible in mechanically ventilated classrooms. Teachers had flexible policies for clothing and allowed students to add or remove sweaters as needed. Even in uniform schools, teachers only enforced closed-toe shoe policies for Physical Education classes and allowed a more relaxed clothing code during the hottest times of the year. On the other hand, some

teachers brought sweaters for themselves and adjusted their clothing when the AC was feeling too cold for them.

In all districts, teachers mentioned that children were sometimes cold inside the classroom during the summer with typical summer clothes. Since teachers could not adjust the AC setpoint, they allowed children to wear a jacket inside the classroom if necessary to avoid complaints:

"Then you know, they're, they're wearing sweaters and it's 110° outside, so they do, they complain about it, often." (Teacher D, Desert district)

"The kids all bring their jackets even in August, because it can get really cold in the classroom and then they're going in and out." (Teacher F, Inland district)

A teacher in the Coastal district speculated that the factors causing these sensations had two origins. First, the place where children sat in the classroom (localized comfort), and second, the temperatures children were accustomed to at home:

"I think they forget that it gets cool when we first come back together, because I don't think most of my students have air conditioning at home, so they forget that it does get cool at some point. So sometimes they'll bring sweatshirts and... And it depends too on where they sit. When you're right underneath the vent they get a cooler shot, so those kids will bring something like a sweatshirt or a jacket." (Teacher J, Coastal district)

This suggests that children's thermal sensations are influenced by factors extending beyond the classroom, including their personal history, cultural background, and family context. Similar ideas have been exposed over the years and led to the creation of the adaptive comfort model (Brager & de Dear, 2003). By removing all adaptive opportunities from occupants in mechanically ventilated schools, the differences in expectations and comfort sensations become salient, calling out for a more nuanced approach to classroom design.

Portable controls

As buildings are designed to restrict teachers' ability to adapt, some bring additional controls to their classrooms. The most common addition were portable fans to create air movement during the summer. Across all districts, teachers were permitted to bring their own fans for air circulation and in some cases the districts provided them. In addition, other controls like portable air cleaners added during the COVID pandemic were present in most classrooms, but many teachers weren't using them consistently anymore.

Some adaptations were not permitted but still practiced by teachers. For instance, personal heaters were prohibited in all districts due to the risk of tripping electrical circuits. Nonetheless, a teacher from the Inland district admitted using a personal heater all year long, even during the summer, because her classroom was too cold, and she lacked control over the AC:

"Because, when we're teaching here in the summer. It's like the district, it's like the district office I think controls the air. And so, in the summertime, they make it really cold. And so, I've even had to use it in the hot summer months." (Teacher F, Inland district)

Other teachers mentioned bringing air fresheners or diffusers to mask student's body odor, and none of them thought of ventilation as a strategy to remove the smells and increase IAQ in their classrooms. This calls out for the education of teachers regarding IAQ and thermal comfort, so they are aware of other strategies that may help with these issues without causing damage to the existing systems, or which might generate irritation or allergies for vulnerable students.

5.3.2.2. Teaching and learning adaptations

Teachers' primary concern for teaching and learning revolved around high temperatures. They all agreed that if the classroom became too hot, students' ability to learn would be compromised. However, most stated that this wasn't an issue in their classrooms, except when the AC malfunctioned. Teachers mentioned that when classrooms became too hot, students had difficulty concentrating, felt tired, sluggish, lost interest in paying attention, and became irritable, all of which aligns with previous literature

(Wargocki & Wyon, 2017). Additionally, teachers said that if they felt too hot, teaching became more difficult as they sweated when moving around the classroom, losing focus and making it harder to maintain student engagement.

To improve student comfort, teachers adjusted their classroom conditions or modified their teaching practices. For example, one teacher mentioned dimming the lights to create the illusion of a cooler environment and opting for a movie instead of a regular lesson, when cooling the classroom wasn't feasible.

"They'll tell me: Can you make it cooler? Can you turn the air on? Can you? Can we like, like we do this whole thing, like, sometimes I'll just turn off the lights. You know, because sometimes that'll cool off the room a little bit, yeah, so." (Teacher H, Coastal district)

Additionally, a few teachers implemented behavioral adaptations such as allowing more bathroom breaks for students to cool off or reminding them to bring and fill their water bottles to stay hydrated during class. In addition, teachers recognized the need for a period of adaptation and cooling down after students returned from recess, in some cases they even used breathing exercises before starting the lesson to regain their attention.

In all schools, children were not allowed to modify the classroom environment without asking their teacher, and were only allowed to perform personal adaptations, which is consistent with prior research (de Dear et al., 2020). Typically, most requests were related to thermostat adjustments, while requests for other adaptations like opening windows were nonexistent. Teachers stated that students appeared not to be aware of the possibility of opening windows to modify the environmental conditions of the classroom.

"No, I mean, no student has asked to change it for like their preference. That no student has kind of asked or has even said: Could I open a window? Could I? To do anything like that." (Teacher G, Coastal district)

Instead, students resorted to personal adaptations like wiping their faces, drinking water, fanning themselves, or standing next to a fan to cool down. However, some teachers discouraged them from doing it, as they had the preconception that these adaptations would not help increase their comfort:

"[When students are feeling too hot] They lose focus. They want to put their head down because they're hot, and they want to fan themselves and I'm like, that's not going to do any good, it feels good, but it's just going to… you know, your body temperature is still raised." (Teacher J, Coastal district)

Since the pandemic ended, the importance most teachers gave to ventilation in classrooms has diminished. They only associated ventilation with the schools' emergency mode and were not concerned by other air quality issues (e.g. pollen, particulate pollution, mold, etc.), or the influence of IAQ on student learning. Only one teacher expressed curiosity about understanding the IAQ of her classroom and wanted to have monitors to help assess various pollutants that could potentially affect her students' health:

"Yeah, to kind of see or a graph and see like, oh, it's today more… There are more particles in the classroom than yesterday, is it on a day where there was the grass got cut today. So, I'm getting more pollen in the class. So, it's in my carpet. So, you know I, I don't. We don't have anything like that here for monitoring. […] Because at home I'm conscious of my air quality and that's why I got an air filter for home, and here I felt comfortable with this one. But having a device monitoring your particles in the classroom would also… that would be ideal, yeah." (Teacher E, Inland district)

The importance teachers give to IAQ in their classrooms comes from personal perceptions instead of general knowledge and clear protocols to deal with IAQ problems. Therefore, continuously reinforcing teachers' education on the importance of IAQ beyond the pandemic is a need across all schools.

5.3.3. Maintenance Managers and Classrooms

5.3.3.1. Typical Planning and Execution

"We always joke in maintenance that we have a plan until the phone rings. We plan to go and do all these tasks in the day, and then the phone rings and that changes our plan, so it's those unexpected work or emergencies that throw us off track." (Maintenance manager, Coastal district)

Managers assess school facilities' conditions to prioritize maintenance needs. They send supervisors to inspect the schools and, in some cases, may outsource equipment diagnostics for easier prioritization. Maintenance is then categorized as deferred or general based on needs, budget, and district's response capacity. All the districts that participated in this research had a work order system for schools to request maintenance services and used spreadsheets to keep track of their maintenance practices. However, day-to-day emergencies pose significant challenges for districts, depleting budgets, time, and staff resources, despite managers' planning efforts:

"So, each November we meet all the maintenance managers, myself, from their assessments over the previous years and we prioritize which, which projects should go first, and based on the budget that we have […] there's always emergencies that, that happen, that aren't on our deferred maintenance plans, like we'll have a water main break, and that was, no one knew that was going to happen. So, some of those funds come from our deferred maintenance budget, and we're not able to execute some of that other work because of this, unforeseen issue." (Maintenance manager, Coastal district)

Trades personnel from each district handle these emergencies. All managers agreed that their trades personnel were their greatest strength, as they had the ability to respond quickly and effectively to crises. This allowed them to feel confident of the good condition of the schools under their care. However, they all faced capacity issues to deal with the amount of work that school facilities demand:

"My people are, are very skilled trades personnel. Our weaknesses, I don't have enough of them. Just by the sheer volume of what I've got to maintain, we need to be very selective on projects that are not directly related to the maintaining the facility." (Maintenance manager, Inland district)

"At this school district we have a lot of good talent in the trades. I'm lucky out here in the desert I can pull from some pretty talented air conditioning guys and plumbers, and electricians. So that, that's good. They're very good at emergency response, putting out the fires and stuff like that." (Maintenance manager, Desert district)

One of the main differences between the districts was in their preventative maintenance approach. While the Inland district had an established written plan, the Desert and Coastal districts had general maintenance practices but lacked a formal preventative maintenance plan. The Coastal and Desert managers said their primary focus was "putting out fires", and only performed preventative maintenance when time allowed, which left systems unchecked until something malfunctioned.

In addition, even if the work order system keeps a record of maintenance needs, addressing, and closing the requests, as well as keeping a record of systems' performance and condition still represents a challenge, and is a necessary step for long-term planning:

"What tends to happen too is there's a failure in the replacement in an air conditioner, and we haven't been effective at capturing that new data when we put a new air conditioner in at a site that has aged equipment, we haven't been effective at capturing that change. It doesn't close that loop back up for the asset that was installed, it's a big challenge." (Maintenance manager, Coastal district)

However, there are strategies that can help managers keep better track of the work that is being done at the school sites. According to the Inland maintenance manager, having this documentation entirely online and in the cloud has allowed them to share reports on the state of different maintenance processes directly with the schools at any time, which represented a valuable tool to keep track of the different trades and prioritize different kinds of projects:

"We run it on a spreadsheet. Everything, everything's on a spreadsheet. We moved from Excel to Google, and I like Google because we can share it with everybody. We, you can be a read only, you can be an editor, you can be an owner. But when safety calls me and says, hey, I've got a problem with this classroom. I just share the document with him. Here's what we've done, and that's through all my fire, life safety, my sprinklers, my fire risers, my back flows, you know, all of that, I… Hey, I need this. Hang on. Boom! And I send it to him, you know. We really are trying to get away from paper. We scanned everything, put it in the Google Doc. And we share it across platform." (Maintenance manager, Inland district)

Aside from budgetary constraints, managers require additional staff to address preventative maintenance for the long-term sustainability of their systems. In the districts that don't have a preventative maintenance plan, the challenge to create one lies in the delayed results of this kind of approach. Effective preventative maintenance may initially slow immediate responses to emergencies as resources are allocated to maintenance tasks. However, implementing and adhering to a preventative maintenance plan could ultimately reduce the frequency of emergencies by addressing issues before they escalate.

5.3.3.2. Emergency Response

COVID-19 Impacts on School Infrastructure

Sufficient funding for maintenance and operations is one of the most prevalent challenges across districts. During COVID, as funding sources from the Federal Government became available for schools coming from the Coronavirus Aid, Relief, and Economic Security (CARES) Act, such as the American Rescue Plan Elementary and Secondary School Emergency Relief funds (ARP ESSER I, II and III) (California Department of Education, n.d.), districts had a way to improve their facilities to adapt to the emergency. A report from 2022 showed that schools' second highest planned spending from ESSERIII funds was air filtration, HVAC and cooling, closely followed by repairing or improving school facilities to reduce the risk of illness (Center for Green Schools, 2022).

Adapting school facilities to the COVID-19 emergency posed challenges for all districts, which were identified early in the pandemic and were prevalent in many school buildings (The Center for Green Schools & ASHRAE, 2021). One of the main constraints managers faced was the age of the equipment, which couldn't accommodate the recommended MERV 13 filters. Consequently, they had to find alternative solutions based on the limitations of each system. In some schools, HEPA standalone air cleaners were installed in classrooms to enhance existing filtration capabilities. In others, they modified the existing filters by connecting various filters to create panel filters and achieved MERV 11 without compromising the existing system. This represented an ingenious solution to a problem that otherwise would have required completely changing the system. In the words of one of the managers:

"Since COVID the big push we had from the industry has been to go to MERV 13 or above. A lot of the equipment can't handle that. It's too much of a, a differential pressure drop across that filter, and so it finds another way around the filter which is not good. You're not filtering. So, we, at this point we reached a happy medium with a filter that... They connect all the filters together, and then they oversize it. It's called a panel filter so it fills in all those gaps and seals, so it can't get around the filter [...] It could be two or three filters tied together, so there's no gap between the filters. And we're at MERV 11, and the equipment can handle that, and we don't have any way to call bypass around the filter where we catch everything that we can. So, that's been our kind of our happy medium between the MERV 13, and it used to be equipment pretty much came with the MERV 6 to an 8. It's what they were built for, so we found a sweet spot in the middle that works for us." (Maintenance manager, Desert district).

During the emergency, HEPA filtration became synonymous with safety, providing reassurance to occupants and facilitating the return to classes. While installing filters represented a necessary investment for school districts to ensure the safety of occupants during the pandemic, it also introduced new maintenance needs, which present their own challenges after the additional funding sources are no longer available. Portable HEPA filters and high-grade MERV filters are expensive, require frequent replacement, and often have waiting periods to be received:

"Three times a year we change all the filters at every school site, and that's still a challenge because there's lead times on getting filters. So, what we try to do, is as we finish one rotation out of school, then we'll order filters again that we just replaced to make sure that, even though there's a lead time, we'll be

able to get them in time […] Like those standalone air filters that we talked about, air purifiers, it's $250 to change the filters out of those. Yeah, well, the, the HEPA gets changed out annually, and the pre-filters get changed out three times a year. So, the HEPA filters, are obviously the most expensive component." (Maintenance manager, Inland district).

On the other end, during the pandemic teachers became acquainted with the protocols and strategies promoted by districts to improve IAQ, and many of them still have a standalone air cleaner in their classrooms. However, their attitude towards the filters changed after the pandemic, and the guidance on how and when to use the filters is not clear anymore. During the emergency, teachers had to turn on the filters daily and were preoccupied with complying with school regulations. Now, some teachers see filters as a nuisance that takes up space in the classrooms, and they are becoming a point of friction between maintenance managers and schools:

"Every classroom's got one plugged in, and the, they're supposed to be running them. I can't make the teacher turn them on. We're not pulling them out. I get phone calls all the time. Hey, I want you guys to take this away. We're not pulling them out because it improves our air quality in the classroom." (Maintenance manager, Inland district)

In addition, teachers are unaware of how their filters are being maintained, so they are not relying on them anymore. Some teachers said they didn't think their filters had ever been changed, while others said they were malfunctioning and were not concerned with reporting the issue with the district:

"It's plugged in, and I think it's set in motion. So, it's just plugged in, and nobody told us anything. Nobody's coming to maintain it. If there's a filter that's in it, nobody's changed it." (Teacher J, Coastal district)

"The filter it'll shut off because the filter is dirty. So, it just needs to be changed and they're super quiet. They're, they're just cumbersome, they take up space." (Teacher D, desert district)

As COVID protocols faded and schools' operations returned to normality, this additional infrastructure can provide a safety net for air quality emergencies like wildfires, flu season and other pandemics; or improve IAQ conditions in the presence of other sources of pollution. Nonetheless, it is necessary to develop plans and protocols for teachers to use them, and provide them with sufficient information about their importance and maintenance.

Extreme Weather Events

Climate change is causing extreme weather events to be more frequent. In California, the most critical impacts are temperature increase, unpredictable precipitations, and wildfires (California Climate Adaptation Strategy, n.d.). Schools have aging facilities and equipment that were not designed for such extreme weather events, and struggle to modernize their schools:

"Our oldest school was built; I want to say in the 40s. And our newest schools were built in the early 2000s. So, with the exception of doing some modernization, we don't have any quote "new buildings". And so, we've been, as funding becomes available, every 25 years, school sites are available for funding for modernization and it's, it's a percentage from the state, and it's a percentage from the district. We put that money together and we try to do the most we can for that site, but it's never, it's never a total re-do. And so, we're playing catch up on a lot of our old facilities." (Maintenance manager, Inland district)

In all districts, aging buildings and portable classrooms are not insulated enough for these situations, and older AC systems only work well until the weather reaches three-digit temperatures and very high humidities. Managers in all districts mentioned that during extreme heat, the existing mechanical systems rapidly lost capacity and struggled to adequately cool classrooms:

"Last year was record-breaking heat and we would get hundreds of calls a day for cooling calls. That the system wasn't performing, and sometimes it was the system couldn't perform any better because the humidity was 97% and 98%, and the ambient outside was 110º, so the system wasn't designed to cool a room to 72º when the ambient conditions were so high" (Maintenance manager, Coastal district)

"They [the mechanical systems in the district] perform very well until about 110°. And then if it's 110° and there's any humidity, a lot of the equipment just falls on its face. It just can't keep the room at 76°. And it stays running. We've had, you know, some extremes where the units kept tripping, but that's up at 120°. The equipment is designed to run at capacity until mostly probably by 105°, after 105° it starts losing capacity, and some of it drastically, depending on the age of the equipment, and some of it just flat doesn't want to run at 120°. We keep it running, we reset it, and we do everything we can, but the rooms will creep up to 80°, or better sometimes." (Maintenance manager, Desert district)

In new facilities, districts are modernizing and oversizing their equipment to make it more energy efficient and comply with post-COVID filtration requirements, becoming resilient to IAQ emergencies. However, with existing facilities this is more challenging to achieve. A recent report from the Government Accountability Office (GAO) estimated that about 36000 school facilities in public-school districts needed to update or replace their HVAC systems (U.S. Government Accountability Office, 2020). In addition, the State of Our Schools report from 2021 estimated an underinvestment in school buildings and grounds by 85 billion each year and a subsequent gap of 27.6 billion for Maintenance and Operations (International Well Institute et al., 2021).

The Managers of the three districts faced budget constraints to modernize or replace HVAC systems, as they are one of the largest expenses in school facilities. Therefore, in the cases where they were not able to afford completely new systems, they have to continue upkeeping the older equipment knowing that it does not comply with current standards and may not withstand future emergencies:

"We would install equipment that's compliant with current efficiency standards and EPA and AQMD (Air Quality Management District) requirements, but I can't alter the configuration of the system. It essentially has to be "like for like". (Maintenance manager, Coastal district)

Other kinds of extreme events are harder to foresee and take a high toll on school facilities planning and budget. For example, when hurricane Hillary hit Southern California in the summer of 2023, a few weeks before the interviews were carried out, it caused important property loss and damage in schools in the Coastal and Inland districts:

"When the hurricane came through here, I lost an entire gym floor because my roof leaked. It literally warped my parquet floor, and so because the roof, we, it was slated to be replaced this Christmas, we knew it was bad. We were going after it, I had funding for it, but the rainstorm came through. So, that's expedited not only my roof, but I've got to put a brand-new gym floor in and, and that's an expense I was not expecting to have to pay". (Maintenance manager, Inland district)

"It's very hard to, to hmm foresee that, right? … like, we had a bunch of rain in July, right? we had those storms come through. I did not anticipate that, so we had some more roof damage. Generally, we have those roof leaks and roof issues in January and February so, I thought we were all done and then we had the tropical storm come through. So, those kinds of things, there's no way I could forecast those." (Maintenance manager, Coastal district)

Managers in all school districts have similar issues every year that take a big toll on their budget and prioritization. These situations not only reinforce the importance of having preventative maintenance in older, more vulnerable schools, but also shifting gears towards resilient planning, where school facilities monitor their environment and create buffers to keep schools running even during extreme weather events. An example of this happened in the Inland district:

"Moving forward, you know, where the technology is really advanced, and so, we're putting variable frequency drive units in to maximize our dollar, our electricity use and trying to benefit that way. It may cost me a little bit more now putting those units in, but over the longevity of life for the unit, I'm going to use less electricity. I'm going to be able to cool the place better. Better facilitate and isolate it. If part of the unit goes down, I can isolate a section versus, right now, if my, I had a problem in any of the schools, it's a five finger, the whole school goes out." (Maintenance manager, Inland district)

Managers recognize the significance of this issue and are actively working to modernize their schools as best as they can. However, budget constraints continue to be an issue, and finding the balance between system quality and cost is a point of tension between the multiple stakeholders in charge of managing indoor environmental quality in classrooms:

"We keep abreast of all of it, but you can only, you know, it comes down when they're building a school to dollars. So, a huge chunk is the equipment, and unfortunately public works goes to the lowest bidder, so we spec out, we can spec out the best equipment that we can afford. It's very expensive to build a school." (Maintenance manager, Desert district)

5.4. Conclusions

The relationships between facility maintenance managers, schoolteachers, and the physical environment of classrooms are mediated by a series of interactions that influence indoor air quality and thermal conditions in learning environments. Consequently, each of these relationships can be defined by a predominant theme (Figure 5-4).

The relationship between teachers and maintenance managers is mediated by the efficiency of their communication and prompt response when maintenance is needed. Therefore, this initial relationship can be characterized by the ***communication*** between the two stakeholders. In schools where there was better interactions and more direct communication for the maintenance process, teachers were more positive about their environment, and felt empowered to maintain comfortable conditions for them and the students. On the contrary, in schools where teachers lacked information, or had had poor direct experiences with maintenance, they were frustrated and felt they had no agency over their classrooms. There are tools that can help guide districts in how to manage this relationship, like the Indoor Air Quality Tools for Schools (EPA, 2009), where there are suggestions to create effective communication between maintenance and schools, prevent IAQ problems and reduce distrust.

Similarly, the relationship between teachers and the classroom physical environment is mediated by the ways the adaptations teachers carry out to achieve comfort for teaching and learning, which can happen through building environmental controls, personal adaptations, or additional portable controls. Building environmental controls in classrooms are the result of policy decisions and negotiations, and their use is constrained by school protocols, safety perceptions and occupant preferences. Giving a small degree of control to teachers over the temperature of the classroom (2 degrees) proved successful in school districts to regulate energy use while maintaining occupant comfort, even when these temperatures were different in each location. Similarly, providing mechanisms for teachers to shut down the AC when opening doors

was useful to regulate energy use and provide comfort to teachers and students inside the classroom. Controlled adaptive measures like this one may allow occupants to feel comfortable without compromising energy use.

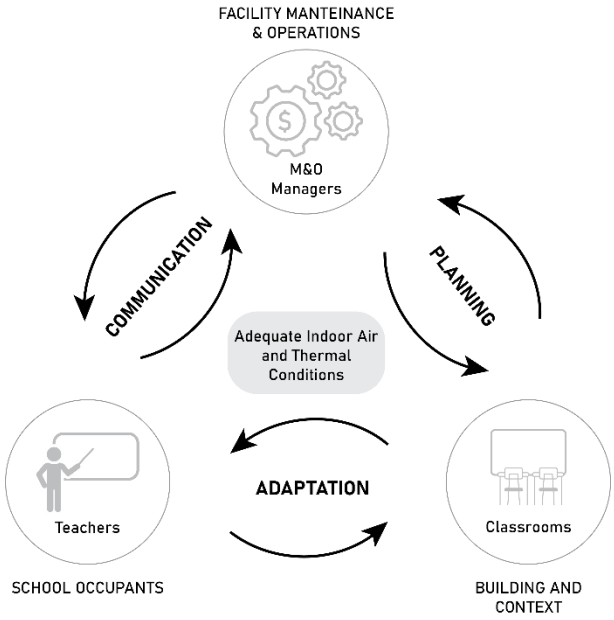


Figure 5-4 Definition of relationships between the three different stakeholders/actors studied in this research and their mediators.

Thermal sensations are personal, subjective, and constructed through personal histories, so personal adaptations occurred in all classrooms, despite being mechanically ventilated. The static model of comfort doesn't account for personal adaptations, but this and previous research has shown that adaptations happen in classrooms of different operation modes (Singh et al., 2019). In this case study, flexible dress codes, behavioral adaptations and modifications to teaching practices were beneficial for the comfort of students and teachers as they helped regulate the impact of heat during the end of the summer.

Most portable controls had to do with the need to feel air movement in the classrooms. The adaptive model of comfort recognizes that comfort can increase with elevated wind speeds in hot conditions (ASHRAE, 2023b), which explains why this kind of adaptations occur. In addition, new research on

personal comfort devices is bringing attention to the use of fans and increased air speeds to achieve comfort (Rissetto et al., 2021). Using fans during the summer or incorporating them in new classrooms as additional building controls could increase classroom environmental comfort. On the contrary, other portable controls, like personal heaters or scent diffusers contributed to the detriment of IAQ and energy efficiency. Monitoring the environment of the classroom and educating teachers about how to use systems more efficiently is key for creating adequate indoor environmental conditions inside classrooms. In addition, teachers' motivations to modify the environment of the classroom showed that they were often not related to temperature or IAQ, but to teaching and learning preconceived ideas. Therefore, creating awareness among teachers of which strategies are more effective, and which are detrimental for their comfort and health is essential for creating optimal classroom environments.

The interactions between adaptations and the classrooms' influences on teaching and learning can be characterized by the idea of *adaptation.* The adaptations described above unveil how thermal and indoor air conditions of classrooms are the result of a negotiation between technical recommendations, local policies, personal preferences and preconceptions, and personal histories. All these aspects play a role in the choices teachers make when adapting to the classroom environment within the constraints they are given.

Finally, the relationship between the classroom's physical environment and maintenance managers is complex. School districts must deal with budget challenges that make maintaining schools a difficult endeavor. Proper documentation of the state of systems is important to provide adequate maintenance services. Similarly, having a preventative maintenance plan and sufficient staff to carry it out can facilitate and reduce the need to cope with day-to-day emergencies in the long run, and make facilities less vulnerable to unforeseen weather events. The increased frequency of widespread emergency situations represents a critical call to action for the urgent need of modernization of aging school facilities and to use equipment that is sustainable in time. Given the existing budget constraints in all districts, it is important to reinforce the planning and monitoring of schools' systems and environmental conditions, to have a clear roadmap of where to direct future investment, and how to operate additional systems engaging the whole school community. A layered approach including administrative measures like use protocols and low-cost technologies to create buffers for the times when systems don't work at their maximum efficiency are key to surpass extreme conditions while school and system modernization is possible.

Creating resilient schools is the goal at which schools and districts must aim for, providing buffers for their systems, and additional options for their classrooms to continue functioning.

Therefore, the relationship between maintenance managers and the classrooms' physical environment is mediated by maintenance daily planning and execution challenges, and the ability of managers to respond to emergency situations. In this sense, this relationship can be characterized by the idea of *planning and monitoring* to create resilient schools for the future. Despite the budget constraints, with better communication, informed adaptations and effective planning mechanisms, schools might be able to create a roadmap to construct resilient IAQ and thermal classroom environments and respond to future emergency situations.

5.5.Bridge

This chapter introduced the qualitative portion of the California schools case study. Chapter 6 acts as a continuation of this chapter complementing the qualitative findings with the quantitative measurements, and revisiting portions of the results included here. It completes the mixed-method approach presented in Chapter 2, unveils the potential of the case study methodology to understand other influences that shape thermal comfort and IAQ in Southern California classrooms.

6. How do Classrooms' Physical Environment, Teachers, and Maintenance Managers Influence Thermal Conditions and IAQ in California?

The case study described in this chapter was conceptualized, developed, written and reviewed by Maria C. Coronado. The manuscript was developed for future publication.

6.1. Introduction

It is well established that thermal conditions, indoor air quality (IAQ) and ventilation can influence cognitive performance in multiple ways including distraction and attention, lack of motivation to exert effort, neurobehavioral symptoms, and acute health symptoms (Wargocki & Wyon, 2017). Studies assessing thermal comfort and IAQ developed in schools have mainly considered the environmental conditions of classrooms in conjunction with student perception surveys, as they are considered the most important occupants in schools.

However, recent reviews of thermal comfort studies have pointed out that in schools, it is often teachers who have control over the environment instead of students (de Dear et al., 2020; Singh et al., 2019). This might be due to classroom or school rules, such as asking for the permission of the teacher to open a window or wearing certain items of clothing in a uniform (de Dear et al., 2020). This happens especially in primary school classrooms, as younger students do not take any adaptive actions on their own, and have been found to be less sensitive to temperature changes than older students (Singh et al., 2019). While this finding comes from adaptive comfort studies, similar behaviors have been observed in students in classrooms of different ventilation modes. In mechanically ventilated buildings teachers may have control of the thermostat or of children's ability to change their clothing level in the classroom (Singh et al., 2019). Therefore, understanding teachers' behaviors and actions in classrooms might be important to understand classrooms' comfort conditions in mechanically ventilated classrooms as well.

In addition, in mechanically ventilated classrooms, building systems play an essential role in providing optimal indoor air quality and ventilation. Previous research has found that classroom ventilation rates are often too low when compared to the standards. Average CO_2 concentrations are often similar in

mechanically ventilated and naturally ventilated classrooms, proving that the problem expands throughout ventilation modes (Fisk, 2017). In the US, 31% of public schools use one or more non-permanent buildings (IES-NCES, 2023), which is problematic because while early studies showed no significant differences between CO_2 concentrations between portable and permanent classrooms (California Air Resources Board, 2003; California Air Resources Board & California Department of Health Services, 2004), more recent studies show that portable classrooms present higher CO_2 accumulations and lower ventilation rates than permanent classrooms (Chan et al., 2020; Mendell et al., 2013). In addition, a 2020 report estimated that about 36,000 school facilities in the country needed to update or replace their HVAC (U.S. Government Accountability Office, 2020).

It would be expected that newer or retrofitted heating, ventilation, and air conditioning systems (HVAC) would improve ventilation in classrooms. However, a recent study in California schools found that recently retrofitted classrooms were often too hot and allowed for the accumulation of CO_2, not providing adequate ventilation compliant with current ASHRAE or California Title 24 standards, suggesting that replacing older equipment does not immediately guarantee optimal ventilation in classrooms. This occurs due to installation and operation problems, as well as insufficient routine maintenance and lack of CO_2 monitoring (Chan et al., 2020). Similarly, a Finnish study found correlations between upgrades to the HVAC systems and airflow measurement, ventilation rate per student and per area, and mean temperature, indicating the need for regular adjustment, maintenance, upgrade or replacement of faulty HVAC systems (Toyinbo et al., 2016). The US Environmental Protection Agency (EPA), in its Indoor Air Quality Tools for Schools makes a case for the development of an IAQ program that helps schools manage and maintain IAQ in their facilities (EPA, 2009). Understanding systems, and how they are maintained and operated is also crucial to achieve adequate indoor environmental quality classrooms.

Lack of ventilation is problematic because it allows for the concentration of pollutants from organic and inorganic origin in enclosed spaces. For instance, particulate matter $PM_{2.5}$ and PM_{10} are classic pollutants found in urban settings that are common in schools (Mendell & Heath, 2005), and have been associated with cardiovascular disease, respiratory disease and lung cancer (Chen & Hoek, 2020). Sources of indoor PM can include chalk-board dust resuspended dust from children's activity, cleaning, and combustion from heating, among others, while outdoor sources usually include traffic, industrial emissions, and wild fires (Sadrizadeh et al., 2022). Both sources play a role in schools' IAQ, and the relationship with indoor and outdoor PM metrics is sometimes related and sometimes it's not (Salthammer et al., 2016). Therefore,

it is important to understand a schools' context and general physical environment to assess probable $PM_{2.5}$ and PM_{10} sources.

In addition, schools with more facility condition issues, in higher need of repair, especially those related to IAQ (mold, poor ventilation, vermin, humidity, poor ventilation, building system condition problems) have been found to be significantly related to absenteeism. Also, schools from lower socioeconomic districts, minority students, and with younger students have been associated with higher rates of absenteeism (Eitland, 2020; Simons et al., 2010). This might be explained by the fact that on average, local school districts are responsible for only about 45% of their annual operating budget and 82% of their capital budget, which makes poor and low-wealth districts frequently unable to adequately maintain their buildings and grounds, or modernize their schools properly (Filardo et al., 2019). Even during the pandemic, when federal funds became available to support the safe operation of schools, a report found that larger districts and districts with a higher percentage of free and reduced-price lunch eligibility (FRPL) were less likely to implement multiple IAQ measures in all schools, while districts with high percentages of white students were more likely to have implemented them (The Center for Green Schools & ASHRAE, 2022). This study uses a mixed methods approach to understand the influences of teachers' adaptations, management decisions and the classroom on the thermal comfort, ventilation and IAQ performance of 12 low socioeconomic status classrooms in Southern California.

6.2.Methods

6.2.1. Case study schools

The study was carried out in three School Districts in Southern California in September of 2023: one on the coast, one inland, and one on the desert. The names of the districts and the schools who participated in the study were replaced with pseudonyms to protect their privacy. All districts are in different climate zones according to the Köppen Geiger classification. The Coastal School District is located in a warm summer mediterranean climate (Csb), the Inland School District is in a hot summer mediterranean (Csa), and the Desert School District is in a hot desert climate (BW). Typical September temperatures for each school district were taken from weather files from stations near the schools are presented in Table 6-1, with data taken from the CBE Clima tool (Betti et al., 2023).

Table 6-1 Typical September temperatures in each school district

	Temperatures (ºF)			
	Max	Min	Mean	sd
Desert	104.6	72.2	88.5	40.6
Inland	102.9	54.0	74.4	44.3
Coastal	93.9	57.0	70.5	39.8

Two schools were selected in each district to carry out the study (6 schools total). This was done with the help of Facility Managers to ensure the schools had a majority of low-socioeconomic status students. In the Desert and Inland schools, over 96% of the students were eligible for free or reduced-price meals (FRPM), while in the Coastal district this was the case for over 66% of the students (California Department of Education, 2024). Also, the most recent California Department of Education's School Accountability Report Cards (SARC) showed that all the school facilities were in good condition, rating the Desert school facilities as "exemplary", and the Inland and Coastal schools as "good" (California Department of Education, 2023).

Of the six schools, five were elementary or K-8 schools, so the selected classrooms ranged from first to fifth grade. In these classrooms teachers and students stayed in the classroom during most part of the school day, which was beneficial for thermal comfort and ventilation calculations. Only School I3 was a high school, so the selected classrooms had different characteristics from the rest of the sample (Table 6-2). In each school, two classrooms were selected to carry out the study, for a total of 12 classrooms. Since the selected schools had classrooms of different types and conditions, these were purposefully sampled to represent this variability. In four schools, one portable and one permanent classroom were measured concurrently to represent these differences. The remaining two schools didn't have portable classrooms. In addition, the sample included permanent classrooms in different conditions, which had been retrofitted at different times, including upgrades in their HVAC systems. Four different classroom conditions were identified: (1) New classrooms built in the last 5 years, (2) Recently retrofitted

classrooms, modernized in the last 10 years, (3) Old classrooms retrofitted in the 1990s, and (4) Old portable classrooms from the 1990s (Table 6-2). Modernizations in the classrooms included upgrades to their HVAC systems in all cases. School D2 in the Desert district was a new building, so the 2 selected classrooms were new. Similarly, School I3 in the Inland district was being torn down and rebuilt on-site by stages, so the selected classrooms were one old classroom scheduled for demolition in the following months, and one new classroom. All classrooms were air conditioned and working normally during the research, except for classroom I in School C6, which had a malfunction in the HVAC system and was running with fans and opening one door and one operable window at the time of the study.

A minimum of three visits to each school were made to gather information on the classrooms. Student and classroom use data was collected through interviews with the teachers in each classroom. In addition, observations and pictures noting different elements of the classroom environment were gathered during these visits.

Table 6-2 Classroom sample characteristics

District	School	School type	Classroom	Grade	Type	Condition	Last retrofit date	Number of students	Height of equipment m (ft)
Desert	D1	Charter K-8 School	A	3rd	Permanent	Old retrofit	1990s	27	0.8 (2.6)
			B	5th	Portable	Old portable	1990s	29	1.1 (3.6)
	D2	Elementary School	C	2nd	Permanent	New building	2019	22	1.1 (3.6)
			D	2nd	Permanent	New building	2019	25	0.8 (2.6)
Inland	I3	High School	K	Science lab	Permanent	Old retrofit	1990s	varies	1.1 (3.6)
			L	Fab lab	Permanent	New building	2022	varies	1.1 (3.6)
	I4	Elementary School	E	3rd+4th	Portable	Old portable	1990s	23	1.2 (3.9)
			F	2nd	Permanent	Recent retrofit	2010	19	1.2 (3.9)
Coastal	C5	Elementary School	G	5th	Portable	Old portable	1990s	32	1.6 (5.3)
			H	1st	Permanent	Old retrofit	1990s	26	0.85 (2.8)
	C6	K-8 School	I	2nd	Permanent	Recent retrofit	2019	25	1.2 (3.9)
			J	5th	Portable	Old portable	1990s	32	1.15 (3.8)

6.2.2. Physical measurement protocol

Physical measurements took place for a full week (7 days) in the Desert and Coastal districts, and for a school week in the Inland District (4 days). Indoor sensors were placed inside a small crate on the side of the classrooms to avoid bothering the normal development of classes (Figure 6-1). Since the crate was placed on top of existing furniture, the measuring height varied from classroom to classroom, ranging from 0.8 m (2’ 7.5”) to 1.6 m (5’ 3”) (Table 6-2). However, it was generally placed around the breathing zone of children following the directions of ANSI/ASHRAE Standard 62.1 - 2022, Ventilation and Acceptable Indoor Air Quality (ASHRAE, 2022a). All sensors were calibrated and/or tested according to manufacturer's guidelines before the starting the study to verify their accuracy.

Three different sensors were placed inside the crate to measure thermal comfort and indoor environmental quality variables: CO_2, Temperature, Relative Humidity, $PM_{2.5}$ and PM_{10} (Table 6-3). To calculate the mean radiant temperature (MRT), a 4 cm (1.5”) diameter ping pong was attached to a thermocouple and suspended in the middle of the crate to measure globe temperature. A Testo hotwire anemometer was used to measure the air velocity inside the rooms for 3 minutes, following the directions of the ANSI/ASHRAE Standard 55-2023 Thermal Environmental Conditions for Human Occupancy (ASHRAE, 2023b), for thermal comfort calculations.

An additional sensor was placed outside in each school to track $PM_{2.5}$ and PM_{10} outdoor concentrations (Figure 6-2). The orientation of the selected classrooms in each school varied, as sensor placement depended on the availability, type and condition of classrooms (Figure 6-3). Maximum and minimum outdoor temperatures and relative humidity values for each day were taken from nearby airport weather stations.



Figure 6-1 Indoor sensors inside a crate inside a classroom.



Figure 6-2 Outdoor air quality sensor location

Table 6-3 Sensor specifications

Sensor	Measurement	Precision
HOBO MX1102 CO_2 logger	CO_2 (ppm)	0 to -5000 ppm. ±50 ppm ±5% of reading at 25°C (77°F), < 90% RH (non-condensing) and 1,013 mbar
	Temperature (ºC or ºF)	0° to 50°C (32° to 122°F). ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F)
	Relative humidity (%)	1% to 90% R.H. (non-condensing). ±2% from 20% to 80% typical
HOBO U12 -12	Temperature (ºC or ºF)	± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F)
	Relative humidity (%)	± 2.5% from 10% to 90% RH typical, to a maximum of ±3.5% including hysteresis at 25°C (77°F); below 10% and above 90% ±5% typical
HOBO TMC6-HA Cable	Globe temperature	Range: -40 to +212F Accuracy: +-0.9ºF at +70ºF (-41°C to 20°C)
Purple Air Zen Air Quality Monitor (indoor and outdoor)	$PM_{2.5}$ and PM_{10}	Laser particle counters: Counting efficiency 50% at 0.3µm & 98% at ≥0.5µm. Effective range ($PM_{2.5}$ standard): 0 to 500 µg/m³
	Outdoor temperature (ºC or ºF) and relative humidity (%)	Temperature range: -40°F to 185°F (-40°C to 85°C) Humidity: Response time (τ63%): 8s. Accuracy tolerance: ±3% RH Hysteresis: ≤1.5% RH

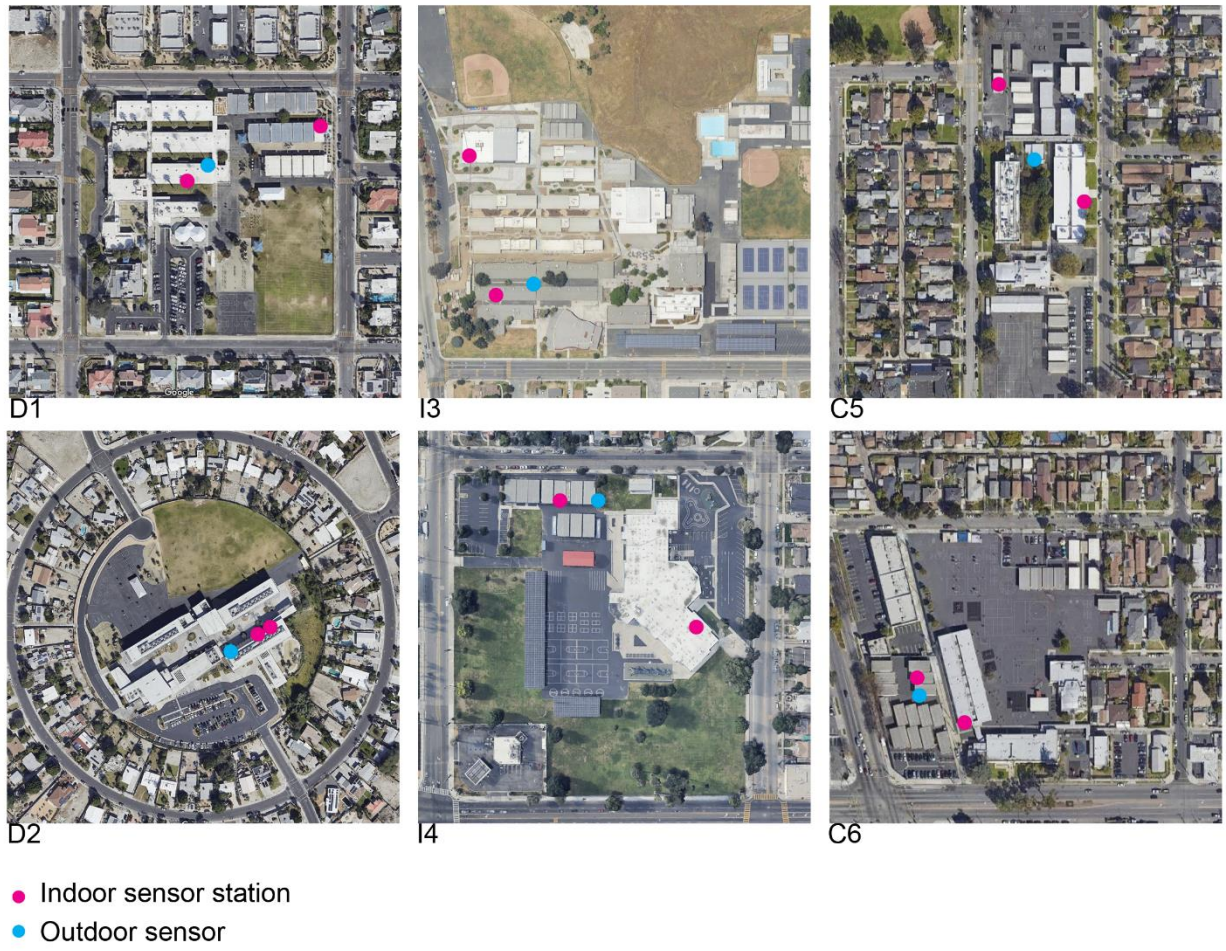


Figure 6-3 Schools and sensor station locations in each building (north up).

6.2.3. Teacher and facility manager interviews

To complement the quantitative data from the physical measurements, the teachers from each of the measured classrooms were interviewed on their thermal comfort and air quality perceptions of the school and classroom. The interviews lasted 20 to 30 minutes. Teachers in the Inland high school (I3) did not participate. In addition, Facility Maintenance Managers participated in a 40 to 50 minute interview inquiring about their role in the school district in relation to thermal comfort and indoor air quality in classrooms. All interviews were transcribed, coded and the codes were grouped by themes for subsequent analysis. The relevant details related to the thermal controls and ventilation in classrooms are included here, as they are vital for the analysis and discussion.

6.2.4. Thermal comfort analysis

Since all the participating classrooms were mechanically ventilated, thermal comfort measurements were analyzed following the static model of comfort or Predicted Mean Vote (PMV) model, of the guidelines from ANSI/ASHRAE Standard 55-2023. Mean radiant temperature (MRT) was calculated from globe temperatures using the procedure from the ASHRAE Handbook of Fundamentals-2021 (ASHRAE, 2021), and then used to calculate operative temperatures according to the ANSI/ASHRAE Standard 55-2023.

Indoor temperature measurements were logged every 5 minutes. However, to understand the thermal conditions of classrooms only during class time, temperature and relative humidity measurements were filtered between 8 am and 4 pm, to represent typical class hours in each district. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indexes were calculated from the logger data for every classroom using the CBE comfort tool (Tartarini et al., 2020).

To visualize the thermal comfort zone, the measurements were displayed in the psychrometric chart using the ggpsychro package for RStudio, which allows the user to plot custom temperature and relative humidity data to the chart (Hongyuan Jia, 2019). The comfort zone was extracted from the CBE Comfort Tool for the current ASHRAE Standard-55 (ASHRAE, 2023b; Tartarini et al., 2020). To define the comfort zone, a metabolic rate of 1.4 MET was established for children, following the data provided by previous studies (Batterman, 2017). Clothing values were selected according to the observations done during fieldwork and visits to the schools, and the general recommendations of the CBE Comfort Tool (Tartarini et al., 2020). For the desert district, a CLO of 0.5 was used, while in the Inland and Coastal Districts, clothing insulation value was increased to 0.57. Analyses in the psychrometric charts are presented by type and by condition of the classroom in each school district.

6.2.5. Ventilation analysis

The most recent version of the ASHRAE Standard 62.1-2022 in its “Addendum ab” presented new recommendations for maximum CO_2 above ambient concentrations when implementing CO_2 Demand Control Ventilation (DCV) (ASHRAE, 2023a). For classrooms, the standard recommends a maximum

CO_2 concentration above ambient of 600 ppm. Therefore, assuming an ambient concentration of 400 ppm, the maximum CO_2 concentration of classrooms with DCV would be 1000 ppm, which is a benchmark used in previous literature to indicate appropriate ventilation (Chan et al., 2020; Fisk, 2017). In this study, measured CO_2 concentrations and distributions were compared with this benchmark for different types and conditions of classrooms. In addition, only Monday to Friday 8 am to 4 pm measurements were considered for comparison with the1000 ppm benchmark. Carbon dioxide logs from classroom K in school I3 were removed from the CO_2 analyses due to sensor malfunction. Wilcoxon-Mann-Whitney U tests were used to compare CO_2 concentrations between portable and permanent classrooms in each district, and a Kruskal-Wallis test with pairwise comparisons using Dunn tests was used to assess CO_2 concentrations between classroom conditions.

Ventilation rates (VRs) were calculated for all classrooms to compare them with findings of previous studies. To calculate VRs, the initial 5 minute measurements were averaged to 15 minute intervals, following a similar approach to previous studies (Batterman, 2017; Chan et al., 2020; Mendell et al., 2013). Only elementary classrooms (1st to 5th grade) were included in this calculation, as their occupancy was more constant than in high school classrooms. Like the previous analysis, only class time measurements were considered. The CO_2 emissions per person for children that were used depended on the grade level of each classroom, and were taken from the CO_2 generation rates calculated by a previous review, which uses 1.4 MET of physical activity for children sitting quietly, studying, taking notes and writing (Batterman, 2017). In the case of the classroom with students from 3rd and 4th grade, the average CO_2 generation rate between grades 3rd and 4th was used. Finally, to account for the teacher, CO_2 emissions for one adult at 1.7 MET (0.46 L/min-person) were weighted with the maximum occupancy of students in each classroom.

The steady-state method presented in a previous review (Batterman, 2017) was used to calculate the ventilation rates in each classroom. Therefore, ventilation rates were calculated using equation 1:

$$VR = (1.67\ x\ 10^4)\ Gp\ /\ (C_S - C_R) \qquad (1)$$

Where VR is the outdoor air flow rate per person (L·min−1·person−1), Gp is the weighed CO_2 generation rate of children and teacher in each classroom, C_S is the peak 15-minute average CO_2 concentration

(assumed steady-state), and C_R is the outdoor CO_2 concentration, assumed to be 400 ppm, following ASHRAE 62.1-2022 directions for implementing CO_2 demand control ventilation, California Title 24 and the approach followed in previous literature (ASHRAE, 2023a; Batterman, 2017; California Energy Commission, 2022; Chan et al., 2020; Mendell et al., 2013). The results from this equation were compared with a similar approach used in two previous papers looking into ventilation rates in California classrooms, which rendered similar results to a tenth of a decimal (Chan et al., 2020; Mendell et al., 2013).

To estimate steady state conditions, peak CO_2 measurements over a 15-minute period were identified in each classroom for each school day. A visual inspection of the data showed that the highest CO_2 average did not always represent a steady state condition, similar to what has occurred in previous studies (Chan et al., 2020). This occurs due to changes in occupancy during class hours, and the fact that class changes occur at about the same time as ventilation rates in schools. This is a limitation as it can bias the VR calculation (Persily, 2017). This approach can make VRs higher than they are for moments when the CO_2 is increasing, and lower for moments when outdoor airflow is provided as acknowledged in previous studies (Chan et al., 2020). In a previous review, the transient mass-balance method provided the most accurate results for calculation, when time-varying attendance is known (Batterman, 2017). However, this study didn't use this method, as detailed 15-minute occupancy of the classrooms was not monitored due to logistical limitations. Therefore, the study follows the approach by Chan et al., 2020 where they used the steady state method to calculate ventilation rates and compare their results with previous studies like the one by Mendell et al. 2013. In Chans' study argues this is possible as despite the existing limitations, the difference between the transient-mass method and the steady-state method in Batterman's review was only 10% (Batterman, 2017).

6.2.6. Particulate matter ($PM_{2.5}$ and PM_{10}) analysis

Indoor and outdoor particulate matter measurements ($PM_{2.5}$ and PM_{10}) were collected every 2 minutes and then averaged to every 5 minutes to match the CO_2 and temperature databases. Particulate matter data was cleaned, organized, analyzed and graphed using RStudio (R Core Team, 2021). Only concentrations between 8 am and 4 pm were considered in the analyses to understand its effect only during class times.

Since the data was not normally distributed, Wilcoxon-Mann-Whitney U tests were used to find differences between indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations. In addition to these comparisons, Kendall correlations were run to test for the monotonic behavior of indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations. Similar to the ventilation analysis, Wilcoxon-Mann-Whitney U tests were also used to compare $PM_{2.5}$ and PM_{10} concentrations between portable and permanent classrooms in each district. In addition, a Kruskal-Wallis test followed with pairwise comparisons using Dunn tests was used to assess indoor particulate matter concentrations in classrooms of different conditions.

In all comparisons, particulate matter concentrations were contrasted with the WHO short-term 24-hour recommended concentrations in their Global Air Quality Guidelines (AQG) (WHO, 2021), and the National Ambient Air Quality Standards (NAAQS) from the Environmental protection Agency (EPA) in the United States (EPA, n.d.). The AQG recommends a level of 15 μg/m3 of $PM_{2.5}$ and a level of 45 μg/m3 for PM 10 as the target 24-hour concentrations, while the NAAQS recommends 35 μg/m3 for $PM_{2.5}$ and 150 μg/m3 for PM_{10}.

6.3.Results

6.3.1. Thermal comfort assessment

During class hours, classrooms were comfortable for about 60% of the time, according to the ASHRAE Standard 55-2023. Classrooms tended to be slightly cooler than the standard, as shown in Figure 6-4, where the distribution of data is off centered from zero, towards negative values that go beyond -0.5 in the PMV index. However, on average, the Predicted Percentage Dissatisfied (PPD) for all classrooms was 11% (Table 6-4).

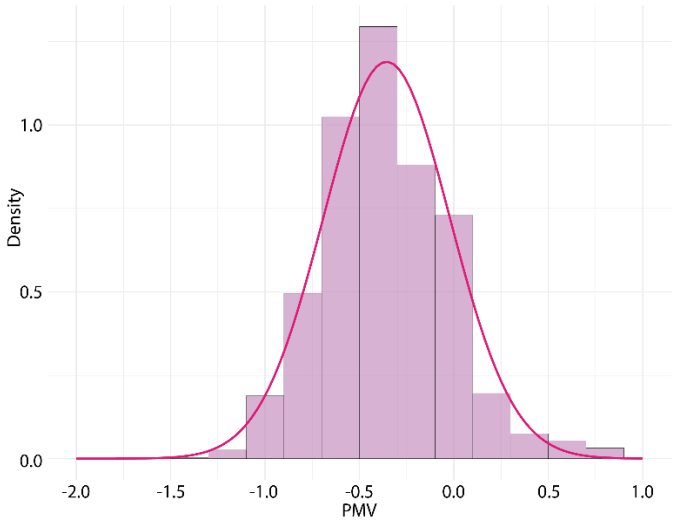


Figure 6-4 PMV for all classrooms in the study

Psychrometric charts per district, constructed by type and by condition revealed that in the Desert district, classrooms in permanent buildings were inside the comfort zone (Classrooms A, C, D). On the contrary, the portable classroom (B) was slightly overcooled (Figure 6-5a). When looking into the influence of classrooms' conditions, the classrooms in School D2, which were both in a new building, had a different pattern than the permanent classroom in School D1 (Classroom A), an old retrofit (Figure 6-5b). Classrooms in School D2 allowed temperatures and relative humidity values to vary widely, having minimum and maximum values of 66.3 º F to 80.8º F for temperature and 37.6 % to 69.9 % for relative humidity, showing a scattered pattern, but always staying inside the comfort zone. On the contrary, the old retrofit had a more compact behavior, maintaining a narrower band of temperatures (74.0 to 76.1 ºF) and 41.7% to 56.6 relative humidity (Table 6-4).

In the Inland District, both permanent and portable classrooms were inside the comfort zone (Figure 6-5c). This was the only district with 4 different classroom conditions, and where they were inside the comfort zone most of the time (Figure 6-5d). Even more, the recent retrofit (Classroom F), was inside the comfort zone during 91% of school hours.

In the Coastal District the thermal behavior of classrooms of different conditions was similar to the Desert District. Permanent classrooms were inside the comfort zone, while portable classrooms were overcooled

during a portion of the school day (Figure 6-5e). In this case, classrooms in permanent buildings, whether they were recent or older retrofits performed better than portable classrooms. The HVAC in the recent retrofit (Classroom-I in School C6) wasn't functioning during the week of measurements. This might explain why it presented a steady increase in temperature along the relative humidity curve in the psychrometric chart (Figure 6-5f). Nonetheless, the classroom remained inside the comfort zone during 80% of school hours (Table 6-4).

Table 6-4 Descriptive statistics of thermal variables and thermal comfort indexes.

			Temperature (°F)				Relative humidity (%)				PMV			
Ds	Sc	C	Min	Max	Mean	Med	Min	Max	Mean	Med	Time in discomfort	Time in comfort	PMV (avg)	PPD% (avg)
D	D1	A	74.0	76.1	75.0	75.0	41.7	56.6	48.42	48.58	33%	67%	0.41	15.0%
		B	70.0	76.3	71.9	72.3	38.3	49.4	43.68	43.80	57%	43%	-0.47	10.4%
	D2	C	71.7	80.4	74.5	74.8	37.6	69.9	49.89	50.71	35%	65%	-0.27	11.3%
		D	66.3	80.8	73.6	73.8	38.9	79.7	57.53	57.82	60%	40%	0.12	16.6%
I	I3	K	69.9	79.2	73.8	74.3	46.8	61.2	52.27	52.50	28%	72%	-0.36	9.1%
		L	69.6	74.8	73.3	72.8	53.9	64.8	58.08	58.44	13%	87%	-0.29	7.3%
	I4	E	70.6	77.7	74.2	74.2	40.1	54.3	45.88	46.18	22%	78%	-0.29	7.8%
		F	70.6	73.0	72.1	72.1	50.2	61.4	54.64	54.92	9%	91%	-0.31	7.2%
C	C5	G	67.8	73.1	71.4	71.3	47.9	72.3	62.88	62.10	78%	22%	-0.46	13.9%
		H	70.1	73.8	72.9	72.8	41.8	69.4	50.22	54.56	8%	92%	-0.23	7.8%
	C6	I	70.6	80.5	73.8	74.4	47.6	63.6	57.52	57.23	20%	80%	0.02	7.7%
		J	67.6	71.8	70.4	70.1	46.4	59.6	52.14	52.06	75%	25%	-0.43	14.2%
											40%	60%	-0.19	11.9%

Ds = School district, Sc = School, C = Classroom.

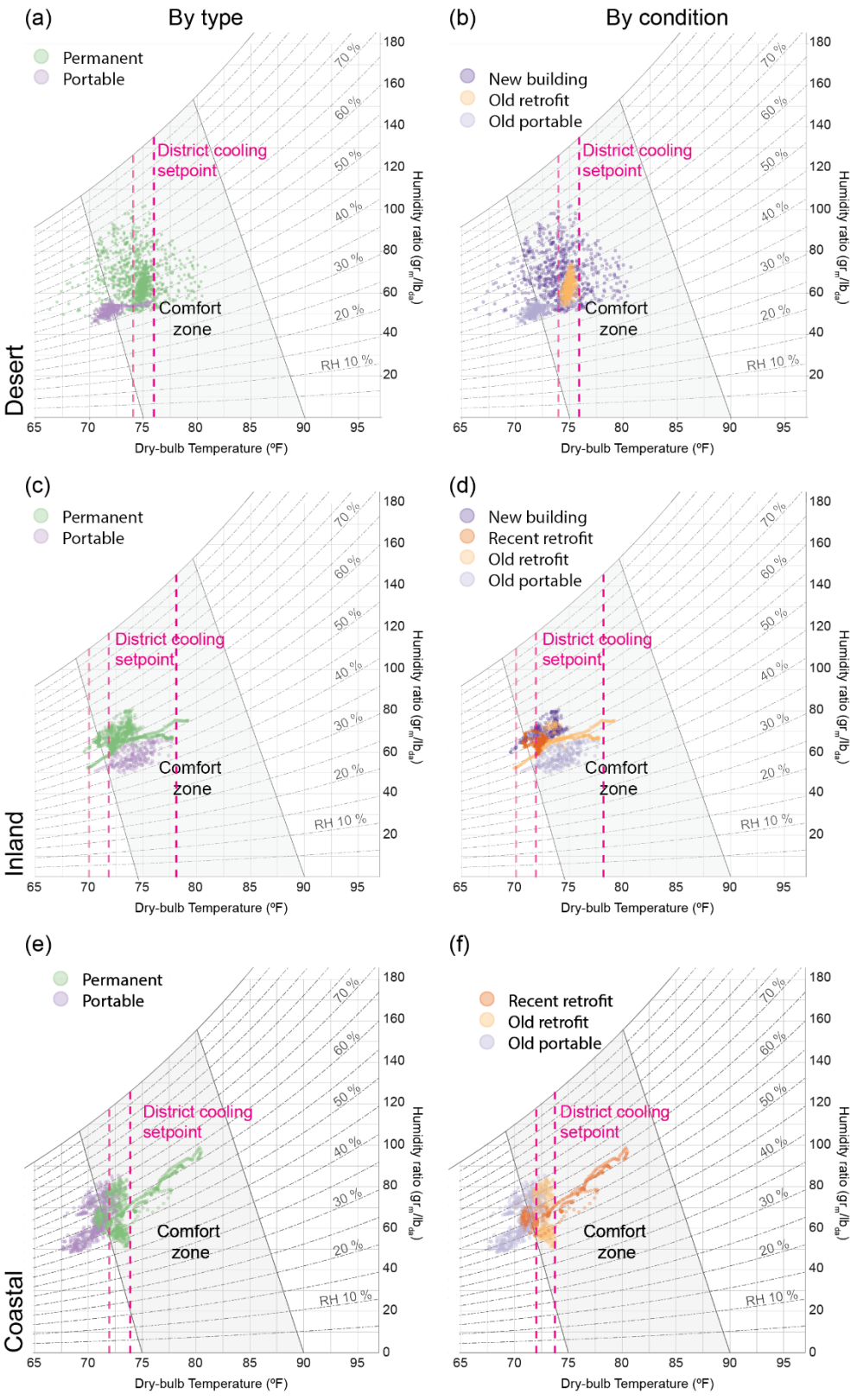


Figure 6-5 Psychrometric charts for each district by type (a, c, e) and condition of classrooms (b, d, f).

6.3.2. Ventilation assessment

To assess differences in CO_2 concentrations between portable and permanent classrooms, Wilcoxon-Mann-Whitney U tests showed significant differences at the $p < 0.001$ level in all districts (Table 6-5). Portable classrooms had significantly higher concentrations when compared to permanent classrooms (Figure 6-6m). In addition, a Kruskall-Wallis test revealed significant differences in CO_2 concentrations in classrooms of different conditions. Old portable classrooms had the highest median CO_2 concentrations, followed by old retrofits, recent retrofits and new buildings (Figure 6-6n). Follow-up pairwise comparisons using Dunn showed differences occurred in all pairs, except for the pair between new buildings and recent retrofits.

Table 6-5 Wilcoxon-Mann-Whitney U tests show differences between types of classrooms.

	CO_2 (ppm)	
District	W	*p*
Desert	50177	<0.001*
Inland	2149	<0.001*
Coastal	90923	<0.001*

Portable classrooms were on average 88% of the time above the 1000 ppm threshold, reaching an average maximum of 3812 ppm among the 4 classrooms. Two of the new classrooms (L and C) only surpassed the threshold 1% of the time. The remaining new classroom was above the threshold 64% of the time (D) despite being in the same building as classroom C. The recent retrofit in the inland district was within the threshold 100% of the time, while the retrofitted classroom where the HVAC was malfunctioning (I) was above the threshold 72% of the time. Old retrofits had a varying performance. In the desert district classroom A was above 1000 ppm 90% of the time, while classroom H only surpassed it in 26% of the CO_2 readings (Table 6-6).

Table 6-6 CO_2 concentration descriptive statistics by classrooms and comparison with the 1000 ppm benchmark for ventilation.

District	School	State	Room	CO_2 concentrations						
				Max	Min	Mean	Median	SD	> 1000 ppm	< 1000 ppm
Desert	1	Old retrofit	A	3373	559	1834.1	1824.5	591.2	90%	10%
		Old portable	B	4555	632	2423.4	2363.0	792.8	98%	2%
	2	New building	C	1056	380	676.1	678.0	145.5	1%	99%
		New building	D	1752	484	1113.7	1092.0	272.3	64%	36%
Inland	3	New building	L	1008	399	727.4	729.0	148.6	1%	99%
	4	Old portable	E	3187	640	1856.6	1881.5	605.7	86%	14%
		Recent retrofit	F	662	409	544.1	562.0	59.1	0%	100%
Coastal	5	Old portable	G	2507	416	1470.2	1541.0	537.3	76%	24%
		Old retrofit	H	1363	396	779.9	738.0	246.0	26%	74%
	6	Recent retrofit	I	2860	497	1221.5	1209.0	448.4	72%	28%
		Old portable	J	5000	517	2657.0	2761.0	1090.0	91%	9%

During the peak 15-minute average CO_2 concentrations (estimated equilibrium) for each classroom during a class day, portable classrooms reached mean CO_2 concentrations over 3231 ppm, while new buildings had the lowest average concentrations (1260 ppm). In portable classrooms ventilation rates dropped to an average of 1.6 L/s-person. In portable classrooms ventilation can be done using the operable windows on the front and back of the classroom. Of the sample, classroom F (recent retrofit), was an outlier where the ventilation rates were very high, with a minimum of 14.4 L/s-person (Table 6-7).

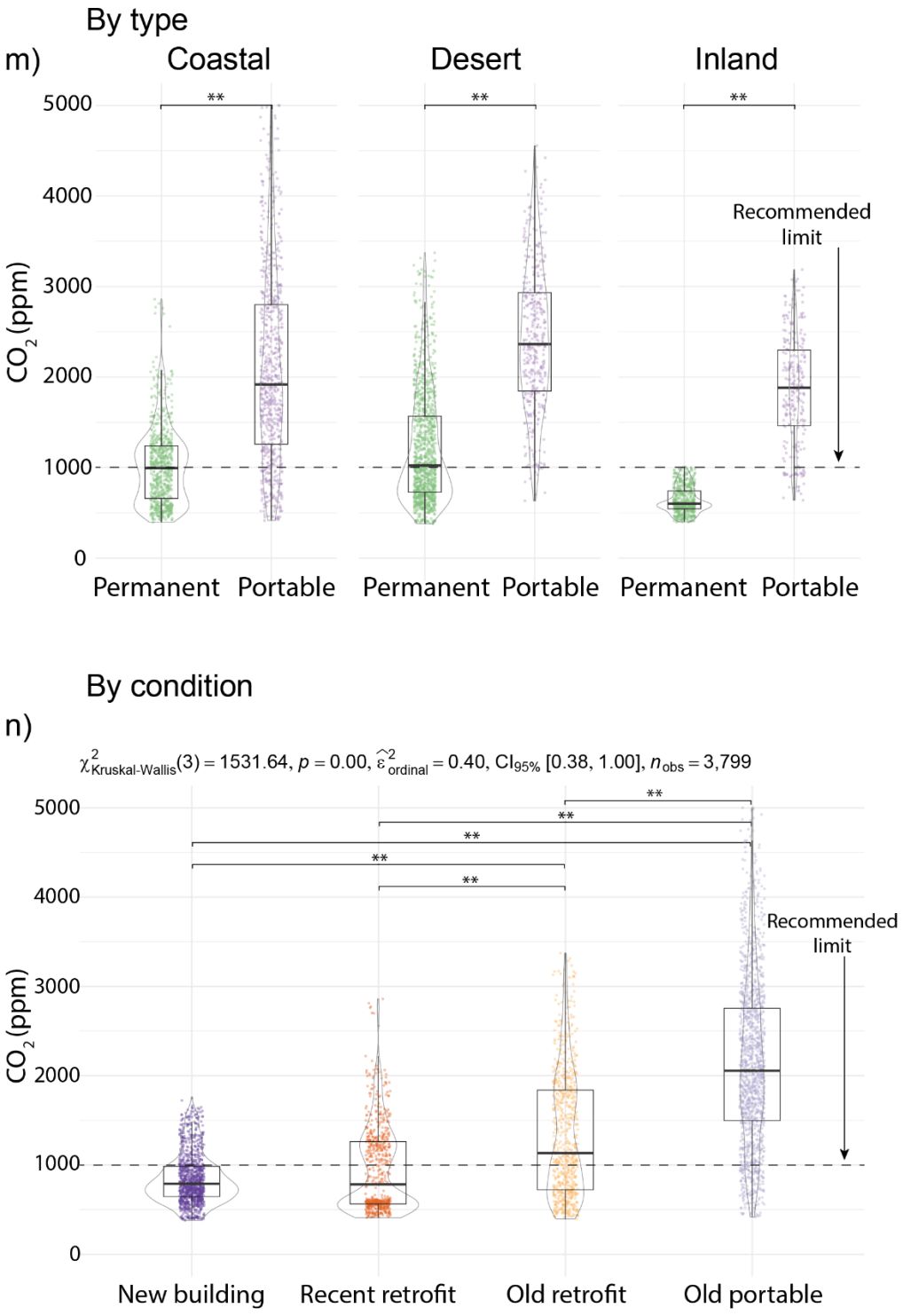


Figure 6-6 CO_2 concentrations by type (m) and by classroom condition (n).

***Indicates significant differences.*

Table 6-7 Peak (estimated equilibrium) indoor CO_2 concentrations and ventilation rates calculated by classroom, classroom type and classroom condition

	Peak (estimated equilibrium) CO_2 concentration (ppm)					VR (L/s-person)				
Room	CO_2 peak (min)	CO_2 peak (max)	Median	Mean	SD	VR (min)	VR (max)	Median	Mean	SD
All	603.67	4846.67	2095.83	2180.29	1181.9	0.94	16.84	2.33	3.84	3.95
By Classroom										
A	2294.3	3278.0	2887.2	2836.7	458.3	1.26	1.91	1.47	1.53	0.30
B	2874.7	4338.3	3847.7	3727.1	617.7	1.07	1.70	1.22	1.30	0.27
C	811.0	988.0	961.5	930.5	81.7	5.78	8.27	6.06	6.55	1.17
D	1521.7	1680.0	1578.8	1589.8	74.6	2.64	3.01	2.87	2.85	0.18
E	2506.0	2968.7	2605.7	2693.4	243.5	1.48	1.80	1.72	1.67	0.17
F	603.7	637.7	624.5	621.9	17.1	14.43	16.84	15.28	15.52	1.22
G	2121.7	2411.7	2309.3	2288.0	138.0	2.08	2.43	2.20	2.23	0.17
H	834.0	1317.3	1045.3	1060.5	244.1	3.41	7.21	5.24	5.27	1.94
I	1356.0	2070.0	1711.0	1712.0	306.2	2.02	3.53	2.60	2.69	0.65
J	3381.3	4846.7	4049.3	4081.7	780.0	0.94	1.40	1.18	1.18	0.25
By Condition										
New building	811.0	1680.0	1254.8	1260.2	359.8	2.64	8.27	4.40	4.70	2.12
Old portable	2121.7	4846.7	2968.7	3231.2	904.3	0.94	2.43	1.48	1.59	0.48
Old retrofit	834.0	3278.0	1805.8	1948.6	1008.4	1.26	7.21	2.66	3.40	2.38
Recent retrofit	603.7	2070.0	1356.0	1244.8	621.7	2.02	16.84	3.53	8.19	6.91
By Type										
Permanent	603.7	3278.0	1356.0	1494.9	764.8	1.26	16.84	3.41	5.31	4.51
Portable	2121.7	4846.7	2968.7	3231.2	904.3	0.94	2.43	1.48	1.59	0.48

6.3.3. Particulate matter ($PM_{2.5}$ and PM_{10}) assessment

Descriptive statistics showed a mean $PM_{2.5}$ of 7.65 µg/m3 and a PM_{10} of 8.62 µg/m3 in all classrooms during class time, with an average indoor/outdoor ratio of 0.4 for both pollutants (Table 6-8). In all districts, Wilcoxon-Mann-Whitney U tests showed significant differences between indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations (Table 6-9). Outdoor PM concentrations were significantly higher than indoor $PM_{2.5}$ and PM_{10} concentrations in all districts (Figure 6-7g and h). In the Inland and Coastal districts, outdoor concentrations were also higher than the WHO AQG of 15 Ug/m3 for 24-hour exposures during school hours (Figure 6-7g). In addition, in all districts indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations were significantly and positively correlated (Table 6-10).

A similar analysis of the difference between permanent and portable classrooms using Wilcoxon-Mann-Whitney U tests revealed that in the Coastal and Inland districts, permanent classrooms had significantly higher $PM_{2.5}$ concentrations than portable classrooms, even when portables had the highest outliers (Table 6-9). In the Desert district, no significant differences were found (Figure 6-7i). For PM_{10} concentrations, all districts showed significant differences between portable and permanent classrooms (Figure 6-7j). Median concentrations $PM_{2.5}$ and PM_{10} concentrations in the three districts didn't surpass the WHO 24-h air quality guidelines or the NAAQS recommendation. Nonetheless, portable classrooms showed the highest outliers indoors exceeding the recommended AQG limit in the Coastal and Desert Districts.

For different classroom conditions, Kruskal-Wallis tests for $PM_{2.5}$ and PM_{10} revealed significant differences in all pairwise comparisons using Dunn. The highest $PM_{2.5}$ and PM_{10} outlier values came from old portable classrooms. Only outliers surpassed the WHO 24-h air quality guideline in classrooms of all conditions during the measuring week (Figure 6-7k and l).

Table 6-8 $PM_{2.5}$ and PM_{10} descriptive statistics

	$PM_{2.5}$					PM_{10}				
	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min
By location										
Inside	7.65	3.68	12.11	252.07	0.00	8.62	4.54	12.44	113.73	0.00
Outside	18.10	16.62	12.92	56.17	0.28	23.27	21.48	16.44	68.97	0.49
By type										
Permanent	7.54	5.72	9.13	252.07	0	8.38	6.41	8.66	102.95	0
Portable	7.87	0.96	16.51	187.29	0	9.10	1.77	17.71	113.73	0
Outdoor	18.10	16.62	12.92	56.17	0.28	23.27	21.48	16.44	68.97	0.49
By condition										
New building	4.14	2.65	4.23	19.39	0.04	4.77	3.04	4.49	20.77	0.09
Old portable	7.87	0.96	16.51	187.29	0.00	9.10	1.77	17.71	113.73	0.00
Old retrofit	8.64	7.96	9.08	33.42	0.00	9.47	8.51	9.69	36.81	0.00
Recent retrofit	11.45	8.65	12.56	252.07	2.84	12.62	9.78	9.72	102.95	3.00
By district										
Coastal	18.27	15.10	17.03	252.07	0.00	21.16	17.58	18.92	113.73	0.00
Inland	13.13	10.46	9.51	36.89	0.00	14.84	11.09	11.41	49.56	0.00
Desert	3.00	1.54	4.36	44.31	0.00	5.35	2.34	9.46	71.26	0.00

Table 6-9 Wilcoxon-Mann-Whitney U tests showing differences between location of measurement and type of classroom

	Location (In-Out)				Type (Permanent-Portable)			
	$PM_{2.5}$		PM_{10}		$PM_{2.5}$		PM_{10}	
School District	W	p	W	p	W	p	W	p
Desert	160011	<0.001*	151511	<0.001*	218058	0.9123	194222	<0.01*
Inland	17460	<0.001*	14860	<0.001*	219193	<0.001*	218620	<0.001*
Coastal	196506	<0.001*	176247	<0.001*	362421	<0.001*	366198	<0.001*

Table 6-10 Correlations between Indoor-Outdoor $PM_{2.5}$ and PM_{10} measurements

District	School	Indoor - Outdoor	tau		N
Desert	1	$PM_{2.5}$ - $PM_{2.5}$	0.4192315	*	768
		PM_{10} - PM_{10}	0.3385541	*	768
	2	$PM_{2.5}$ - $PM_{2.5}$	0.5882328	*	756
		PM_{10} - PM_{10}	0.5602779	*	756
Inland	3	$PM_{2.5}$ - $PM_{2.5}$	0.5293195	*	594
		PM_{10} - PM_{10}	0.5264883	*	594
	4	$PM_{2.5}$ - $PM_{2.5}$	0.2051712	*	518
		PM_{10} - PM_{10}	0.1975922	*	518
Coastal	5	$PM_{2.5}$ - $PM_{2.5}$	0.2569798	*	687
		PM_{10} - PM_{10}	0.236072	*	688
	6	$PM_{2.5}$ - $PM_{2.5}$	0.2078068	*	741
		PM_{10} - PM_{10}	0.1693741	*	742

*Indicates $p < 0.001$

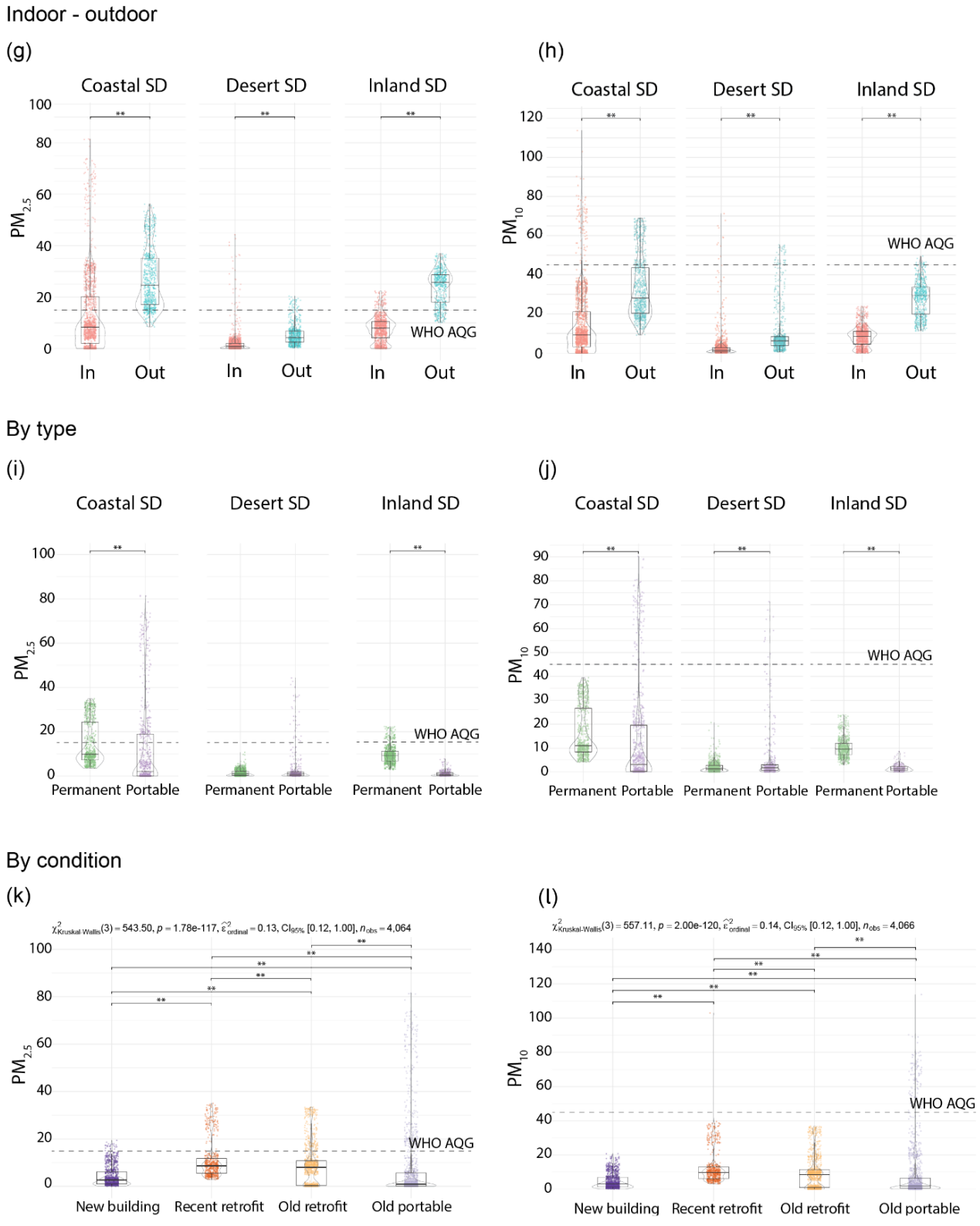


Figure 6-7 Particulate matter comparisons between indoor and outdoor conditions (g and h), classroom type (i and j) and classroom condition (k and l).

6.3.4. Teacher and facility manager insights

Interviews with maintenance managers revealed the influences of district policies in the minimum cooling setpoints for classrooms. In the Desert district, the cooling setpoint for classrooms is 76 ºF, but they allow for lower temperatures on a case-by-case basis, depending on the systems. In the Inland district the cooling setpoint is 72 ºF, allowing teachers to move the thermostat up to 2 degrees down to a minimum of 70 ºF and up to 78 ºF. Finally, in the Coastal district, the setpoint is 74 ºF, allowing teachers to lower the temperatures up to 72 ºF.

In addition, all managers stated that the main source of complaints from teachers came from classrooms being too hot during the summer. On the contrary, ventilation complaints were rare in all districts. The coastal and Inland districts were the 2 larger school districts serving 72 and 84 schools respectively, while the desert district only served 27 schools. All districts did routine and deferred maintenance, but only the Inland district had an official written preventative maintenance plan.

Teacher interviews confirmed the information provided by maintenance managers and presented an interesting point of contrast. Most teachers were unaware of the temperatures in their classrooms and expressed a general preference towards lower temperatures. However, a few teachers stated their desire to be able to shut down the AC when classrooms started feeling too cold at the end of summer. Teachers didn't open windows for environmental control, and many of them had them covered displaying student work for glare control and to avoid students getting distracted during class time (Figure 6-8). Nonetheless, door opening was a common practice to bring in outside air to the classroom. In School D2, classrooms had been equipped with a system that would shut down the AC after a few minutes of having the door open. Teachers stated that using this system when children complained about the classroom being too cold was helpful to turn off the AC for a few minutes and address student comfort.

Teachers' complaints about the classroom environment were mainly directed towards thermal conditions. They considered the AC to be a prized possession to maintain their classroom conditions comfortable. In contrast, air quality and ventilation weren't present in their imaginaries. Body odors from students were their main concern for indoor air quality, and they didn't relate classroom ventilation as a means to help with this issue.



Figure 6-8 Classroom with covered windows to display student work

Teachers in portable and permanent classrooms had similar attitudes and complaints which didn't appear to match the performance of the classrooms. For example, a couple teachers in portable classrooms were very happy with their classrooms, as the air in their classrooms felt "fresh" and "crisp" during the summer. On the other hand, teachers in new classrooms or in recent retrofits complained about the environment of their classrooms being too humid, too cold or too hot at different times of the year.

Teachers performed different adaptations to accommodate to the temperature and air quality in their classrooms. These adaptations included bringing fans, adding odor diffusers, and in one case (classroom F), bringing a small heater and using it even during the summer on occasions when the classroom got too cold inside. In particular, the teacher in classroom-I with the malfunctioning HVAC was very frustrated with her classroom and expressed that additional fans were not enough to reach comfort during the hottest days of the year.

Standalone air filters placed in classrooms during the COVID-19 pandemic were present in seven of the classrooms included in this study, but the current attitudes and ways in which teachers used them varied on a case-by-case basis. Four teachers reported they were not sure if their filters were working properly or if the filters had been changed, so they were either not using them or using them sparsely. One teacher mentioned the filter was too loud, so she used it in the lowest setting. Finally, one teacher mentioned

using the filter only to use the fan, and only one mentioned she still turned it on daily for filtering purposes.

6.4.Discussion

The thermal and ventilation assessments done in this research showed that portable classrooms had significantly poorer performance than permanent classrooms. Permanent classrooms of all conditions, including older retrofits, performed better than portables in the three variables analyzed. In the Desert and Coastal districts portable classrooms were overcooled during the measuring week when compared with the ANSI/ASHRAE Standard 55-2023 and were below the minimum cooling setpoints mandated by the internal policies of their districts. In contrast, permanent classrooms in these districts stayed inside the comfort zone, except for the one with the malfunctioning HVAC. Only in the Inland district portable and permanent classrooms stayed within the comfort zone. Portable classrooms are not thermally insulated as well as permanent classrooms, so they are not good at withstanding increasingly high temperatures. It is likely that the overcooling registered by the sensor in portable classrooms occurs as the AC tries to make up for the thermal losses through the envelope, which is problematic as annual temperatures in California have already exceeded 1°F, with some areas exceeding 2°F with climate change impacts (California Climate Adaptation Strategy, n.d.). This situation places an additional strain on the existing systems and increases the schools' energy use when trying to maintain indoor temperatures within District standards. However, conversations with teachers of portable classrooms, revealed that they were happy with the environment of the classroom, as long as the air felt cool inside, and were unaware of the differences in ventilation between portable and permanent classrooms in their schools.

The thermal behavior of permanent classrooms in each district reflected district policies even more than the current thermal comfort standard. District policies have a narrower band for acceptable temperatures and don't consider humidity ranges, as it is easier to directly relate temperature with comfort sensations in classrooms. Conversations with facility managers revealed that these policies come from negotiations between districts and teachers' unions, which consider teacher's preferences and districts' energy use goals, creating an additional layer to the provision of optimal thermal environments in classrooms.

Districts have created constraints in temperature controls to balance system cooling capacity and energy efficiency. Newer classrooms in California give little to no environmental control to teachers, providing higher efficiency and comfortable conditions most of the time. However, this can become problematic when systems fail and stay unattended for long periods, or when teachers are unhappy with their environment and make uninformed changes. The former became evident in the newly retrofitted classroom in the coastal district, where despite the teacher's efforts to improve comfort using fans, she was often uncomfortable as the classroom HVAC was malfunctioning for over a year, and she hadn't been able to reach out to the district to fix it. In this case, faulty communication between teachers and facility managers, along with restricted controls became the triggers of discomfort. On the latter, when left without any controls, teachers might resort to adaptations that harm the environmental performance of classrooms, or are not energy efficient, such as opening doors while the AC is on, or using a heater inside the classroom during the cooling season. Educating teachers on how the systems in their classrooms work, how to properly tackle discomfort, and providing means to modify classroom conditions without affecting energy efficiency (e.g. increasing indoor temperatures in the end of summer) might help surpass these kinds of situations. For example, the door sensors to shut down the AC implemented in the new school in the Desert district allowed teachers to adjust the temperature of the classroom when children complained that it was too cold, and helped managers maintain energy efficiency in the school. Previous studies have documented similar situations, like a study of hybrid ventilation classrooms in Hawaiian schools where user awareness and training on CO_2 and ventilation significantly impacted the way in which occupants operated the building (Cerri et al., 2020).

Regarding ventilation, portable classrooms in all districts allowed for the accumulation of CO_2 and had low ventilation rates. CO_2 concentrations in portable classrooms surpassed 1000 ppm over 76% of the time and presented ventilation rates as low as 0.94 L/s-person. In contrast, classrooms with new systems kept CO_2 concentrations below 1000ppm during 99% of the time. The calculated mean VRs in all classrooms included in this study was 3.84 L/s-person, which falls in the lower end of those found in previous studies, which ranged from 3.5 to 5.6 L/s-person (Chan et al., 2020; Mendell et al., 2013). It is worth noting that the sample in this study was significantly smaller and included old classrooms, which differs from previous approaches where they looked into classrooms with recent HVAC retrofits (Batterman et al., 2017; Chan et al., 2020). The calculated mean VRs of permanent classrooms in this study were 5.3 L/s-person, and 1.6 L/s-person in portables. However, teachers didn't complain about the air quality in the classroom, as they could not directly perceive the low ventilation. Instead, the most common air quality issue they reported was student body odor, and they resorted to using air scent

diffusers to cover the smell. Managers confirmed this finding, stating that the bulk of teacher complaints came from thermal conditions, and not from air quality. This is problematic, as teachers don't have enough knowledge about ventilation issues and have no way of identifying them. In addition, adding scent diffusers to classrooms may increase VOCs and PM in classrooms (Schwartz-Narbonne et al., 2021), and even influence students' cognitive performance (Du et al., 2022). Future studies could investigate VOCs and other pollutants that were not covered in this research. Teachers tended to resort to these kinds of adaptations mainly after students came back from recess (after playing in the sun) but were not so concerned about body odor resulting from slow and steady changes during the day. Future research could investigate the triggers of these perceptions and compare them with measured IAQ parameters.

The reduced ventilation revealed by CO_2 buildup can affect the health and performance of teachers and children. Previous studies have shown that increases ventilation rates can increase the speed at which children perform typical numerical and language tasks, so reducing them can cause the opposite effect (Wargocki & Wyon, 2017). In addition, reduced ventilation can trap other pollutants in the air produced by indoor sources such as VOCs, PM, and infectious diseases. With COVID-19, classrooms in the 3 districts were equipped either with better filtration in their existing HVAC system, or with standalone air cleaners. However, conversations with the teachers showed that many of them had stopped using the filters as they had not received any guidance on how to use them after the pandemic. In addition, a couple teachers stated that believed their filters were not functional anymore, but they were not concerned about reporting them for maintenance.

Without increased filtration, and lacking enough ventilation, classroom indoor air quality can decrease fast and allow for the buildup of pollutants. While this research didn't find high levels of PM_{10} or $PM_{2.5}$ inside the classrooms, it didn't test for formaldehyde, VOCs, NO2, among other pollutants of organic or chemical origin that have been found in classroom settings in previous research (Daisey et al., 2003; Mendell & Heath, 2005). The filters introduced during the pandemic are assets that complement ventilation in classrooms and can help both during emergency situations like wildfires, pandemics or during common situations like the annual flu season. Educating teachers on systems and issues of environmental quality in classrooms is very important, as the lessons that came from the pandemic are being quickly forgotten inside schools.

6.4.1. Recommendations

This case study showed that not all classrooms are performing above or within the recommended values, and the variations occur from classroom to classroom, even within the same school. While it was expected that newer classrooms and recently retrofitted classrooms outperformed older retrofits, and portable classrooms, the urgency and number of classrooms that need to improve their systems and facilities countrywide is too large to happen in a short period of time.

This endeavor will need a considerable influx of funds, and a massive effort from school districts in terms of time and personnel commitment. Therefore, to tackle some of the issues found in this study, a series of low-cost and organizational strategies may help improve the current indoor environmental conditions in schools by addressing the technical and organizational matters that surround school operation and maintenance from multiple perspectives. This may help address these issues, while school districts are able to fully address the pressing issue of aging schools and systems.

While some problems are harder to tackle with the current state of facilities, like responding to increasingly high temperatures during the summer, other sources of complaints and practices that might create poor indoor air and thermal conditions may be addressed by influencing the use and operation of the space:

- Teacher education and training: One of the salient issues that came up in the study was the disconnect between existing classroom conditions, teachers' awareness of those conditions, and the adaptations they chose to perform to make themselves and their students comfortable. The adaptations depended on the availability of controls, and their own drive to improve the environment. This was problematic in the cases in which these adaptations were ill-informed and went against energy efficiency and/or district policies. Educating and training teachers on how their own classroom systems work and healthy ways to respond to day-to-day situations that may cause discomfort is key for the creation of optimal classroom environments. For example, how to increase ventilation in their classroom to dilute body odor instead of implementing scent diffusers could be helpful for teachers that face these conditions. In addition, with the most recent version of the California Green Building Standards code (CALGreen) requiring schools to include CO_2 monitors in new classrooms with demand control

ventilation (California Building Standards Commission, 2024), it is necessary to train teacher on what CO_2 levels affect, how to tackle high concentrations in their classrooms when they occur.

- Controlled adaptive opportunities: In addition to training, providing teachers with tools that help adjust to situations in which permanent building environmental controls are not enough to keep comfortable conditions for them or for the children. For example, providing options to briefly turn off the AC during shoulder seasons, as occurred in the Desert district, could be an option to increase occupant comfort without hindering energy use when occupants feel classrooms are too cold. Other portable strategies like fans were already present in many classrooms and can significantly increase personal comfort under hot conditions, up to 88 ºF (31 ºC) (Rissetto et al., 2021). The inclusion of these low-cost methods in all classrooms could provide additional means of control that do not significantly increase energy use. Even when fans do not effectively reduce air temperature, they are efficient in improving comfort sensations under hot conditions, and can help teachers move air around the classroom, reducing the sensation of stuffiness. In mechanically ventilated schools, the current operations and maintenance scheme places all the responsibility of environmental comfort on districts' maintenance and operations capacity, and beyond occupant control, making them vulnerable when systems malfunction and can't be fixed immediately. Controlled adaptive opportunities like the examples paired with teacher training can provide a buffer to face times when the main systems are not working, aiding in the climate resiliency of schools.

- Effective communication: Keeping a healthy chain of communication between teachers, school officials and facility maintenance managers is very important for the provision of optimal environments in classrooms. The anecdotal account from the teacher whose AC was malfunctioning and the subsequent decrease in environmental comfort, show that having a recently retrofitted classroom is no guarantee of a good environment if the chain of communication is broken. The Tool for Schools Guide from the EPA touches upon this issue, and provides guidance on how to develop proactive and responsive communication when schools face IAQ complaints (EPA, 2009). In addition, it is recommended that schools and managers revisit and monitor the performance of their own communication system, to verify the effectiveness of communication from teachers to managers and the timeliness of district's responses.

- Clear systems use protocols and planning: The change in attitude from teachers towards the portable filtration systems installed during the COVID pandemic portrays a need for schools and districts to create guidance for schools and teachers on how and when to use portable filters. These can be useful

for events when air quality decreases like wildfire events or to help prevent airborne transmission during flu season.

- Preventative maintenance planning: Preventative maintenance provides a tool to identify equipment issues before they become emergencies. In this study, the Inland district was the only one with a preventative maintenance plan, and it was the only one where classrooms showed a slightly better thermal and ventilation performance. While developing and carrying out a preventative maintenance plan demands staff time and budget resources from school districts, it can increase systems life and performance in the long run, increasing the maintenance capacity of the school district. Preventative maintenance planning can include multiple stages from documenting the state of equipment, creating databases of ongoing maintenance, defining maintenance and operations goals, as well as inspection frequency and maintenance needs (refrigerant levels, leak inspection, filter change, electrical connections, lubrication, pressure, etc.). In addition, having personnel carrying out these maintenance practices can help upkeep HVAC and other systems functioning properly for longer periods.

6.4.2.Limitations

This study has multiple limitations, starting from a reduced sample size, which doesn't allow for generalization, but adds to the body of literature in this area. The findings presented here align with results found in previous literature. In addition, by studying a small number of classrooms and pairing physical measurements with semi-structured teacher and maintenance manager interviews, the study was able to inquire on teachers' adaptive practices in classrooms and relate them with managers' testimonies and classroom conditions, representing a novel approach to the subject. Nonetheless, performing measurements for only a week didn't allow for direct correlations between all the respondents' testimonies and quantitative records. Futures studies could expand the timeframe of the study to a year or more to verify respondents' testimonies with a more robust set of physical measurements. A longitudinal study of this type could bring forward deeper insights on the subject.

Another limitation has to do with the calculation of ventilation rates. Using the steady state method may bias the results of this portion of the analysis, as more accurate methods exist (Batterman, 2017).

Nonetheless, by using this simplified method, we were able to compare the results of this study with previous scholarship.

6.5.Conclusion

This study assessed the thermal conditions, ventilation, and particulate matter concentrations ($PM_{2.5}$ and PM_{10}) of 12 low socioeconomic status classrooms, located in 6 different schools in 3 school districts in southern California, using a mixed method approach. Thermal conditions and ventilation depended on the type and condition of classrooms, with permanent classrooms of all conditions outperforming old portable classrooms. In addition, the study revealed how other influences affect classrooms' thermal conditions, such as local school district policies and teachers' actions to modify the classroom environment.

Reducing teacher control of the environment is an efficient way to provide adequate thermal conditions in classrooms. However, this places all the weight on the managerial system that operates schools, making them highly dependent on the maintenance capacity of school district offices, and leaves occupants without adaptation options when they cannot access maintenance quickly enough. Therefore, communication between teachers and district maintenance managers, as well as building district maintenance capacity become key aspects to maintaining optimal thermal environments in mechanically ventilated classrooms. In addition, providing alternative means of control that don't affect energy efficiency, like turning off the AC when teachers open the door for a few minutes, can be beneficial for both teachers and school districts.

Ventilation rates in most classrooms were on the lower end of those found in previous studies, with a mean of 3.84 L/s-person, allowing for high CO_2 buildup, especially in portable classrooms. In addition, the study revealed that teachers were not using the stand-alone air cleaners consistently, as there was no guidance coming from the school districts on how to approach them after the pandemic. Instead, portable air cleaners in some classrooms are deteriorating, and teachers are not reporting them for maintenance, as they don't consider them necessary anymore.

Finally, the study proposed a series of recommendations and highlighted the importance of addressing the role of teachers and facility managers as key contributors for the creation of better indoor environments in classrooms. Teacher awareness, education, and training on aspects of IEQ are vital for the adequate use of building systems and avoiding behaviors that might hinder the environmental quality of classrooms. In addition, effective communication and sufficient maintenance capacity in school districts are crucial to sustaining optimal conditions in learning environments.

7. Conclusions

The purpose of this dissertation was to characterize the thermal and indoor air quality of low-socioeconomic classrooms and understand how the actions and interactions between teachers and maintenance managers influence those conditions. The findings in each case study highlight the complexity of these relationships, as well as the effect that contextual variables exert over indoor environmental conditions. In addition, the findings expose the complexity of maintaining and using classroom environments, and how daily operations, with inputs from multiple stakeholders can have large influences on the indoor environmental conditions that students and teachers experience in classrooms.

The methodology described in Chapter 2 presented a mixed-method case study approach to understand classroom IAQ and thermal conditions using a mixed method approach. It introduced the idea of including teachers and facility maintenance to study environmental conditions in classrooms through critical elements of schools' operation such as maintenance practices, teachers' use of classroom and its systems, and understanding the interactions between school occupants and facility management and maintenance. The methodology served as the starting point to develop the case studies presented in Chapters 3 to 6, where portions of its methods and tactics were used to assess different aspects of the indoor environment of classrooms.

Chapter 3 investigated the efficiency of natural ventilation strategies to provide sufficient air changes per hour during the COVID-19 pandemic in a classroom in Eugene, Oregon. The study showed that under optimal outdoor conditions, variables like occupancy levels, adaptive behaviors and activities were the main influences on indoor air quality. Indoor $PM_{2.5}$ and PM_{10} concentrations depended on the activities that were being carried out inside the classroom, and only reached problematic levels during cleaning periods, when the students were not in the classroom. In addition, the study showed that teachers' adaptations and school ventilation protocols had a major influence on classroom ventilation, as average CO_2 concentrations decreased close to the target calculated for the pandemic (6 ACH), when all the doors and windows in the classroom were open, allowing for cross ventilation.

The following Chapter examined indoor air quality in naturally ventilated low socioeconomic status schools in Concepción, Chile. The case study introduced a different context, where high levels of outdoor

particulate pollution stemmed from a larger energy poverty issue in the region. It highlighted the need for schools to monitor air quality in the area, as well as to enforce existing policies that address this issue in the region. The study showed that in all schools indoor and outdoor $PM_{2.5}$ and PM_{10} exceeded the WHO Air Quality Guideline, and in some cases, they reached environmental emergency levels according to Chilean regulations thresholds, which are already permissive considering international recommendations. The prevailing use of wood stoves during the winter given the high cost of electricity, caused particulate matter pollution to rise in all schools, with even higher levels in a school located near a major highway. In this case, by measuring indoor and outdoor conditions in classrooms, the study reiterated findings from previous research and problematized the level of concern of teachers about this issue. Survey data revealed that teachers were concerned about acute, immediate environmental influences on health, but were not very concerned about outdoor pollution. With the chronic and prevailing nature of the problem, teachers were accustomed to living in these conditions and did not perceive outdoor air pollution as a pressing health issue. However, the case study couldn't make direct associations between health symptoms reported by teachers and classroom environmental conditions, as other times of exposure were not accounted for. Nonetheless, the study pointed to the need to carry out more comprehensive teacher health studies to account for the impacts of chronic exposures to high concentrations of $PM_{2.5}$ and PM_{10} during and outside class time.

Finally, Chapters 5 and 6 concentrated on the case of 12 low socioeconomic status Southern California classrooms and presented qualitative and quantitative findings respectively. On the qualitative side, Chapter 5 used a grounded theory approach to investigate the relationships between 3 stakeholders/actors: teachers, facility managers and the classroom physical environment, to understand how they interact and co-construct the indoor environmental conditions of classrooms. Through interviews with teachers and facility managers, the study found three main interactions that shaped these relationships for the creation of optimal IAQ and thermal conditions in classrooms. First, effective communication between facility managers and teachers. When the chain of communication is broken or delayed, maintenance issues become more pressing, trust from users diminishes, and environmental quality decreases. Second, teachers' adaptations play a key role in modifying classroom environmental conditions. It is necessary to train and educate teachers on ways to use the systems in their classrooms efficiently and adapt to them without compromising energy efficiency or student health. Finally, the planning and execution of maintenance, along with the ability to respond to emergency situations, also play an important role in classroom environmental conditions. The absence of a preventative maintenance plan was identified as a weakness in two of the districts. In addition, responding to crises, and having well-defined protocols for

foreseeable emergencies like heat waves and the flu season, became important as ways to maintain optimal environmental conditions in classrooms.

Chapter 6 complemented these findings with physical measurements and assessed thermal comfort and indoor air quality inside the same sample of classrooms where the interviews took place. In addition, it revisited some of the qualitative findings presented in Chapter 5 to triangulate the findings of the case study. Physical measurements showed clear differences between permanent and portable classrooms, where permanent classrooms of all conditions outperformed portables. As expected, in permanent classrooms, new buildings presented the highest performance, followed by recent retrofits and older retrofits. These findings align with previous literature and show the urgency of improving the current school facility building stock. By paring these results with the testimonies from teachers and facility managers, it was possible to create a series of recommendations for the operation of school facilities.

7.1. Limitations

The findings for all the studies are case specific, context dependent, and do not allow for generalizations. In addition, in all cases the sample sizes were small, restricted to one or two classrooms per school, which limited the physical measurements and teacher interviews to a small number of spaces and teachers. It is possible that environmental conditions and testimonials of classroom conditions had some variation in other areas of the schools that had different characteristics (e.g. different air handling units, orientations, materials, floor, etc.). A larger sample per school could increase the robustness of future studies.

Another limitation of the case studies has to do with the time of measurement. In the three cases, measurements were taken over the span of a week during the summer in California, winter in Concepcion, and between spring and summer in Oregon. The measurements gathered are only representative of these conditions, not allowing for generalizable conclusions. Previous studies have found that measurements taken in opposing seasons can have well differentiated indoor and outdoor air quality conditions (Habil & Taneja, 2011). In addition, changes in wind and rain patterns, temperature fluctuations, among other weather-related events can change outdoor conditions quickly, and affect indoor conditions as well. It is possible that during winter and summer occupants' perceptions are more focused on temperature, while in shoulder seasons, changes in wind patterns (e.g. Santa Ana winds in California) turn people's attention

towards outdoor air quality. Measuring in multiple seasons and comparing the results would be useful in future studies, as these might portray changes in environmental conditions and perceptions, and open other possibilities for adaptation.

Teachers' perceptions may change depending on the season. In the Chilean case for example, their main health concern had to do with cold temperatures and respiratory viruses during the winter. It is possible that these perceptions would change if the study was repeated during the summer, as perceptions might become focused on other factors that affect health in relation to warmer temperatures. Similarly, during the interviews, teachers spoke from their general experience in the classroom, and recalled experiences that occurred in the past, which were difficult to directly correlate with the measurements taken during a short span of time. Longitudinal studies where teacher's interviews can be directly correlated with long term data collection over the school year would be ideal to solve this issue.

Despite these limitations, the case studies were able to show how low socioeconomic classrooms in different locations have a multiplicity of air quality and thermal comfort issues that in many cases extrapolate beyond the school facility. This dissertation showed that by including the perspectives of teachers and facility maintenance managers, it was possible to unveil other influences of classrooms' thermal comfort and indoor air quality and create recommendations to improve them that come from these sources, in the specific case of each school.

7.2. Implications on Practice and Research

The results from each case study presented in this document have lessons that can be translated to practice and research. Chapter 3 was developed during a shoulder season and showed that under optimal outdoor air conditions natural ventilation can be a good strategy to maintain indoor air quality (assuming good outdoor air quality), if there are enough adaptive possibilities to open the classroom, paired with schoolwide protocols that teachers follow to maintain classroom conditions. By monitoring CO_2 concentrations, schools can oversee ventilation and tackle potential problems during shoulder seasons. Training and educating teachers on protocols to increase ventilation during these occurrences by opening windows, doors, and using fans to exhaust air, can help maintain adequate ventilation of classrooms in cases when outdoor conditions allow for it.

In addition, the recommendations elaborated in Chapters 5 and 6, can be useful to maintain and operate schools. Teacher education and training, additional controlled adaptive opportunities, effective communication, clear systems use protocols and planning and preventative maintenance plans, are strategies that can be directly implemented in schools and school districts to improve the indoor environmental quality of classrooms. While the issue of aging schools and systems in the US is too large to tackle at once, the findings and recommendations presented in these chapters may help schools manage and maintain better indoor environmental conditions in classrooms.

The Chilean case study showed how indoor environmental quality issues sometimes extend beyond the school facility and are harder to tackle. In practice, what would reduce the problem is the adoption and implementation of local policies to improve air quality in the region during the winter. However, while this happens, schools can take action by installing low-cost monitoring systems to protect the health of their students, alert them whenever there is an environmental emergency, and gather data to make a case to pressure the local government into creating incentives for the applications of the strategies proposed in the current Plan for Prevention and Atmospheric Decontamination (PPDA) of the Concepcion Metropolitan region. In addition, implementing ventilation and filtration systems, and decreasing infiltration through window frames, could be beneficial to decrease indoor particulate pollution concentrations. While this case study only scratched the surface of a much larger problem, it pointed at the need to include actions from multiple angles to address it.

Each case study showed how indoor air and thermal conditions in low socioeconomic status schools originate from various sources and can be addressed through approaches and at different levels. These approaches can be framed using an adapted version of the hierarchy of controls used by the National Institute of Occupational Safety and Health (NIOSH). The framework identifies an order of actions to control risk exposures in the workplace that include 1) Elimination: physically removing the hazard, 2) Substitution: replacing the hazard, 3) Engineering controls: isolating people from the hazard, 4) Administrative controls: Changing the way people work, and 5) PPE: protecting people using personal protective equipment (CDC, 2024). Figure 7-1 shows an adapted version of the hierarchy of controls, including recommendations for practice that emerged from the case studies.

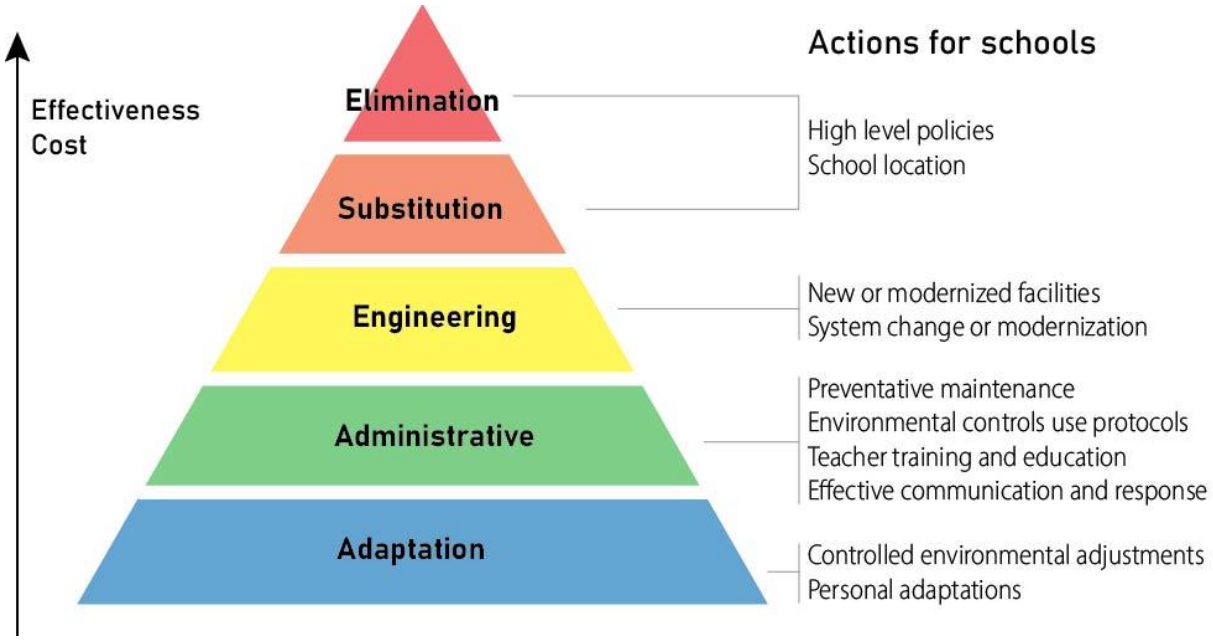


Figure 7-1 Actions to improve IAQ and thermal conditions in schools using the hierarchy of controls framework

The framework recommends starting at the highest level of action and going down from there. However, the initial steps are the hardest to adopt, as they are budget and labor intensive or may be outside the control of the schools or districts. For example, some risks are almost impossible to eliminate, like unpredictable extreme weather events associated with the consequences of climate change. However, in the case studies presented here, actions like local policy changes and implementation, updates in building codes, and school relocation could help eliminate or substitute poor air quality risk. This is the most effective approach, and also the most difficult to achieve. This was evident in the Chilean case, where schools' IAQ was directly correlated with outdoor air quality conditions but is applicable to all cases. In California and Oregon, increasing risks stemming from climate extremes like heat waves, cold snaps, storms, hurricanes, wildfires, floods, among others, are becoming more common, and directly affect thermal conditions and indoor air quality. Therefore, policies geared towards preparing and protecting school facilities against these exposures are necessary.

The next strategy has to do with engineering controls to reduce or prevent hazards. Schools can provide better environments through new or modernized facilities that incorporate more efficient systems, adaptive designs, and redundant environmental control strategies to become resilient to weather and

pollution events. In the case studies presented here, new and modernized classrooms exhibited the best environmental performance, showing the effectiveness of these strategies. Modernization in schools can take many shapes, from building retrofits like increasing thermal resistance, improving infiltration, changing windows, etc., to improving HVAC systems and air filtration. The latter approach is very effective but can be costly and may not be feasible for schools. The challenges to achieve adequate air filtration that schools in California faced during and after the pandemic evidenced the technical difficulties that need to be overcome to make these improvements, even when there is an influx of capital to the school districts. Under normal conditions, schools, especially those with low SES, may not be able to modernize or rebuild their facilities and might need to go down one more level of the framework to be able to improve their environmental quality.

Regarding administrative controls, the case studies showed how preventative maintenance planning, environmental controls use protocols, teacher training and education, and effective communication were critical to maintain the classroom environment healthy and comfortable. In the case of Oregon, protocols and the teacher's commitment to follow them were the main aids to increase ventilation rates in the classroom. In the California case preventative maintenance was necessary to avoid the deterioration of mechanical systems. The case studies showed that engaging the whole school community in the improvement of indoor environmental conditions in classrooms is a bottom-up avenue that is worth exploring further.

The final level can be reinterpreted as personal adaptations and controlled environmental adjustments like fans or turning off the AC. These adaptations need to be provided by the school districts and must be accompanied by use protocols to avoid any negative consequences. In this case, teacher awareness and education are crucial for the adaptations to provide positive outcomes. This level is the widest of the framework because it is the one that could be adopted more easily by schools and teachers at very little cost.

As for research implications, the case studies highlighted the importance of bridging users, management and technical aspects when investigating indoor environmental quality. The studies showed that while understanding the environmental conditions of classrooms was important, it was equally valuable to gather stories from the teachers who experience and control those environments, and the managers who

oversee them off-site. This dissertation showed that mixed-methods and case study research can bring new insights into indoor environmental quality studies, reveal environmental justice issues, and provide tools for schools to tackle targeted thermal comfort and IAQ issues.

7.3. Future Research and Next Steps

Future research opportunities were identified in each case study opening multiple avenues to improve indoor environmental quality in schools, at different levels of control. Chapter 3 pointed at the importance of teachers' actions in a naturally ventilated classroom during the COVID-19 pandemic. Future research could investigate how window and door opening can achieve optimal ventilation in naturally ventilated classrooms when outdoor environmental conditions are ideal and users are engaged, similar to the study by Cerri et al. (2020). In contrast, Chapter 4 presented an example where naturally ventilated classrooms face very high concentrations of outdoor particulate pollution, so natural ventilation is not an option. In this case, future research could investigate alternatives to tackle the sources of particulate pollution, like low-cost replacements for wood stoves or low-cost building retrofits to decrease the need for heating in the winter. In addition, the case study pointed towards the need to develop longitudinal studies that investigate 24-hour particulate pollution exposures in school occupants, to allow for correlations with health symptoms. Finally, further studies could investigate possible low-cost interventions using local technologies, to filter the air and improve indoor air quality in highly polluted classrooms.

The implementation and evaluation of the recommendations that emerged from Chapters 5 and 6 could be investigated by creating interventions in schools and classrooms. Strategies like controlled adaptations in mechanically ventilated classrooms, teacher training, classroom use protocols under different modes, and enhanced communications between managers and teachers can take multiple forms and become interdisciplinary research projects.

It is important to recognize that the increasing pressure derived from climate change like heat waves, hurricanes and other natural disasters, will only become more pressing over time, and create more budget and time constraints to keep school maintenance and operations up to date. Therefore, future research needs to address ways in which schools can become more resilient to potential emergencies. It could evaluate the incorporation of passive strategies and low-energy strategies that can serve as buffers in case

of mechanical systems failure to keep schools running without compromising energy efficiency and indoor environmental quality.

Passive strategies like nighttime ventilation of thermal mass, stack ventilation, transitional spaces, covered, shaded, green outdoor areas, and evaporative cooling, in hot dry places like the desert in California could prove valuable to decrease the energy needs of mechanical systems. In addition, other strategies like increasing air speed through fans can increase occupants' comfort without demanding high amounts of energy. In the case of Chile, strategies like increasing envelope air tightness and improving the thermal resistance of school construction could be investigated as ways to decrease heating needs both in schools and residential buildings. In addition, low-energy strategies like adding portable air filtration can improve indoor air quality in classrooms, under the current (less than ideal) outdoor conditions. Finally, Oregon has seen increasing heatwaves and wildfires in the last years, so a way to address preparedness is to include these strategies in new school designs and school modernizations. In Oregon, passive strategies like the ones proposed for California can be introduced. Assuming good outdoor air quality, all these strategies are feasible options to reduce the strain on mechanical systems, decrease the need for air conditioning in the summer, and run the buildings passively during shoulder seasons.

In addition, protocols and including behavioral, adaptive strategies that are part of building operation protocols are key for the functioning of school facilities. Future schools need to incorporate as many layers as possible from those proposed in Figure 7-1 to fight climate extremes. The integration of passive strategies is necessary to reduce the strain on active strategies, along with a layered approach that considers the behaviors and adaptations of all the stakeholders involved in the management, maintenance, operation and use of school facilities.

The case studies presented in this dissertation highlighted the importance of IAQ and thermal conditions in classrooms, and portrayed how low-socioeconomic status classrooms face different issues vary depending on their context. Including teachers and facility managers' perspectives on indoor environmental quality studies can help understand how they influence and modify classroom environments, and aid in the formulation of recommendations to improve classroom environments. The use, maintenance and operations of classroom spaces are essential factors to consider when striving to create and sustain healthy and resilient indoor classroom environments in years to come.

Appendix A: Observation log

PHYSICAL MEASUREMENT SHEET

GENERAL INFORMATION			
Date start (yyyy-mm-dd)		Date end (yyyy-mm-dd)	
Start time (hh:mm)		End time (hh:mm)	
School name / City			
Classroom name		Children occupancy #	
Teacher name		Teacher occupancy #	
Classroom location		Classroom orientation	
Classroom type		Renewed (Y/N-date)	
Heating system		Width (unit)	
Cooling system		Length (unit)	
Solar control		Height (unit)	
Wall materials		Floor #	
Floor Materials		Outdoor condition to	
Window pane #		Weather	

ONE POINT MEASUREMENT	min 1	min 2	min 3
Windspeed 3min (fpm)			
Outdoor CO2 15 min (ppm)			

EQUIPMENT			
TYPE	NUMBER	HEIGHT	PICKED-UP CHECK
Cage			
Purple Air_Outdoor			
Purple Air_Indoor			
HOBO MX1102A			
HOBO U12-12			
HOBO U-12_TM6 cable			
Router			
Motion			
Door			
Window			

Classroom Plan + Equipment location	
	Observations:
Classroom Section	
	Observations:
Window sketch	
	Observations:

Appendix B: Survey Questionnaire

Q1 Comfort and well-being in classrooms

Researcher: Maria Camila Coronado, University of Oregon
Phone: (541) 650-8324
Email: mcorona6@uoregon.edu

Consent for Research Participation Purpose. This project seeks to understand various factors that can modify indoor environmental quality (IEQ) in classrooms and how these conditions might affect the well-being of school occupants.

Procedures and Activities. You will be asked to comment on your comfort and well-being perceptions in the classroom where you usually teach. About 175 teachers will take part in the surveys conducted in this research. Your participation will last approximately 15 minutes.

Privacy and data confidentiality protection. We will take measures to protect your privacy including (a) The survey responses will be completely anonymous, and (b) All published information will be aggregated data. However, we can never fully guarantee your privacy will be protected.

We will take measures to protect the security of all your personal information, but we cannot fully guarantee the confidentiality of all study information. Protection measures include (a) Data will be collected through Qualtrics and stored securely in the Microsoft One Drive Cloud of the University of Oregon of the researchers, which is password protected and has Duo security, and (b) Only the researchers will have access to the information.

Voluntary Consent. You are being asked to volunteer for a research study. It is up to you whether you choose to participate or not. You may withdraw from the survey at any time or choose not to answer a question if you prefer to. You will not be paid for taking part in this research. You may contact the researcher in the email above if you want to ask questions about any information you don’t understand.

Q2 Statement of Consent:

I have had the opportunity to read and consider the information in this form. I understand that I can ask additional questions throughout my participation by contacting the researcher listed on this form. I understand that I am not waiving any legal rights. I understand that by selecting I CONSENT below, I volunteer to participate in this research.

- I CONSENT to participate in this research
- I DON'T consent to participate in this research

Q3 Classroom Environmental Quality Survey

This research project seeks to create a baseline of environmental comfort and visualize good practices and protocols that achieve adequate environmental quality inside buildings. Thus, it seeks to generate transferable knowledge to interested parties, which can be useful when creating new policies for the design and maintenance of schools, and promote better environments for children, teachers and staff of the school infrastructure.

In the first part of the survey, we would like to know about your responses to the physical conditions of the classroom that you currently teach in and awareness of the mechanical/ventilation systems; in the second part of the survey we will ask about conditions that you may have experienced in the past. You will have an opportunity to write other comments at the end of the survey.

Q4 What school do you teach in? (School name, city, state) _____

Q5 How comfortable is the classroom environment where you teach most of the time?

	Very comfortable	Comfortable	Acceptable	Uncomfortable	Very Uncomfortable
Overall environmental quality	O	O	O	O	O
Temperature	O	O	O	O	O
Humidity	O	O	O	O	O
Ventilation (air movement)	O	O	O	O	O
Sounds	O	O	O	O	O
Daylight	O	O	O	O	O
Electric light	O	O	O	O	O

Q6 In the last school year, how often have you experienced the following factors in the classroom?

	Never	Rarely	Sometimes	Usually	Always
Room temperature, too high	O	O	O	O	O
Room temperature, too low	O	O	O	O	O
Room temperature, fluctuates	O	O	O	O	O
Too little air movement (stagnant/stale)	O	O	O	O	O
Too much air movement (draft)	O	O	O	O	O
Unpleasant odors	O	O	O	O	O
Dry air	O	O	O	O	O
Musty air	O	O	O	O	O
Distracting noise	O	O	O	O	O
Glare	O	O	O	O	O
Dust/dirt	O	O	O	O	O

Q7 What do you think of the overall outdoor air quality surrounding the school in the last school year?

- o Very good
- o Good
- o Acceptable
- o Poor
- o Very poor
- o Don't know

Q8 Are there moments when the outdoor air surrounding the school is not acceptable?

- o Very frequently (daily)
- o Often (weekly)
- o Occasionally (monthly)
- o Rarely (seasonal factors e.g. wildfire)
- o No, never
- o Don't know

Q9 In the past 3 years, are you aware if this school has made any improvements to the:

	Yes	No	Don't know	N/A
Heating	O	O	O	O
Air conditioning	O	O	O	O
Fans	O	O	O	O
Window operation/installation	O	O	O	O
Portable air filters/air purifiers	O	O	O	O
Other	O	O	O	O

Q10 If you answered yes to any of the items above, are these improvements still in use?

- Very frequently
- Frequently
- Occasionally
- Rarely
- Very rarely
- Never

Q11 Please explain the improvements the school made in the box below

_____

Q12 Were there any special practices or protocols in place in the school year 2021-2022 to maintain good indoor air quality and comfortable temperatures in this school? (E.g., Keep windows open all day, monitor CO_2, change air filters more often)

- Yes
- No
- Don't Know

Q13 Please explain the school's practices or protocols in the school year 2021-2022 here

_____

Q14 Are there any special practices or protocols in this school year to maintain good indoor air quality and comfortable temperatures in this school? (E.g., Keep windows open all day, monitor CO_2, change air filters more often)

- Yes, they are the same as in 2021-2022
- Yes, but they are different
- No
- Don't Know

Q15 Please explain the school's practices or protocols in the current school year here

_____

Q16 Do you ever hear complaints from the students about the temperatures or the air quality in the classroom?

- Very frequently (daily)
- Often (weekly)
- Occasionally (monthly)
- Rarely (seasonal factors e.g. wildfire)
- Never

Q17 Describe the most common complaints

_____

Q18 Which of the following have you personally done to change or modify the environment of the classroom for better comfort?

	Yes	No
Add a fan	O	O
Add a portable filter	O	O
Add a portable heater	O	O
Cover the windows to avoid distractions	O	O
Open windows before the students arrive to cool down the classroom	O	O
Bring a CO_2 monitor to the classroom	O	O
Other	O	O
Add a fan	O	O
Add a portable filter	O	O
Add a portable heater	O	O

Q19 What prompted you to make the changes to the environment of the classroom?

_____

Q20 What do you think of the outdoor air quality surrounding the school in the last week?

- o Very good
- o Good
- o Acceptable
- o Poor
- o Very poor

Q21 What do you think of the indoor air quality of your classroom in the last week?

- Very good
- Good
- Acceptable
- Poor
- Very poor

Q22 How satisfied are you in the classroom regarding

	Very satisfied	Satisfied	Neutral	Unsatisfied	Very unsatisfied	N/A
Air conditioning	O	O	O	O	O	O
Fans	O	O	O	O	O	O
Heating	O	O	O	O	O	O
Natural ventilation (windows)	O	O	O	O	O	O
Portable air filters/air purifiers	O	O	O	O	O	O
Indoor air quality in the cool months	O	O	O	O	O	O
Indoor air quality in the warm months	O	O	O	O	O	O
Indoor air quality in the mornings	O	O	O	O	O	O
Indoor air quality in the afternoons	O	O	O	O	O	O

Q23 For each of the following potential issues with indoor air quality and ventilation, please rate how much of a concern it is in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
Unpleasant odors	O	O	O	O	O
Draft	O	O	O	O	O
Stuffy/stagnant air	O	O	O	O	O
Dry air	O	O	O	O	O
Musty air	O	O	O	O	O
Dust	O	O	O	O	O
Other	O	O	O	O	O

Q24 What do you think of the temperature in the classroom in the last week?

- Cold
- Cool
- Slightly Cool
- Neutral
- Slightly Warm
- Warm
- Hot

Q25 How would you prefer the temperature of your classroom in the last week to be?

- Much cooler
- Cooler
- Slightly cooler
- No change
- Slightly warmer
- Warmer
- Much warmer

Q26 How satisfied are you with the following factors in your classroom?

	Very satisfied	Satisfied	Neutral	Unsatisfied	Very unsatisfied	N/A
Temperature in the warm months	O	O	O	O	O	O
Temperature in the cool months	O	O	O	O	O	O
Temperature in the mornings	O	O	O	O	O	O
Temperature in the afternoons	O	O	O	O	O	O
Humidity in the warm months	O	O	O	O	O	O
Humidity in the cool months	O	O	O	O	O	O

Q27 For each of the following potential issues with temperature, please rate how much of a concern it is for you in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
Too cold in the cool months	O	O	O	O	O
Too warm in the warm months	O	O	O	O	O
Too cold in the mornings	O	O	O	O	O
Too warm in the afternoons	O	O	O	O	O
Other	O	O	O	O	O

Q28 For each of the following potential issues, please rate how much of a concern it is for you in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
Outdoor air pollution	O	O	O	O	O
Irritant off gassing from paint/materials	O	O	O	O	O
Respiratory viruses	O	O	O	O	O
Pollen	O	O	O	O	O
Mold/Mites	O	O	O	O	O
Extreme heat wave	O	O	O	O	O
Extreme cold wave / cold snap	O	O	O	O	O

Q29 Have you ever had any of the following:

	Yes, including the last year	Yes, but not in the last year	No, never	Prefer not to say
Asthma	O	O	O	O
Hay fever	O	O	O	O
Eczema	O	O	O	O

Q30 Do you smoke?

- o Yes, often
- o Yes, occasionally
- o Not currently, but I smoked before
- o No, never
- o Prefer not to say

Q31 During the last 3 months, have you had any of the following symptoms?

	Yes, often (every week)	Yes, sometimes	No, never
Fatigue	O	O	O
Headache	O	O	O
Nausea / dizziness	O	O	O
Difficulty concentrating	O	O	O
Itching, burning or irritation in the eyes	O	O	O
Irritated, stuffy or runny nose	O	O	O
Hoarse, dry throat	O	O	O
Cough	O	O	O
Dry or flushed facial skin	O	O	O
Scaling / Itching scalp or ears	O	O	O
Hands dry, itching, red skin	O	O	O
Other:	O	O	O

Q32 For the items where you answered yes, do you believe it is related to your work environment? Explain in the box below

_____

Q33 For each of the following potential issues with sound, please rate how much of a concern (e.g. distraction, annoyance) it is for you in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
Ventilation system (noise from HVAC or fans)	O	O	O	O	O
Outdoor noise (traffic, airplanes)	O	O	O	O	O
School activities outside	O	O	O	O	O
Other	O	O	O	O	O

Q34 For each of the following potential issues with light, please rate how much of a concern it is for you in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
Glare	O	O	O	O	O
Daylight quality/quantity	O	O	O	O	O
Electric light quality/quantity	O	O	O	O	O
Other	O	O	O	O	O

Q35 For each of the following potential issues with general cleaning, please rate how much of a concern it is for you in the classroom where you teach. Mark N/A if the item is not applicable to your classroom.

	N/A	Not at all	A little	Moderate	Big problem
General cleaning is inadequate	O	O	O	O	O
General cleaning is done poorly	O	O	O	O	O
No thorough cleaning is done	O	O	O	O	O
Other	O	O	O	O	O

Q36 How many years have you been teaching at this school?

- Less than 1
- 1 to 5
- 6 to 10
- 10 to 20
- 21 or more

Q37 Do you teach in the same classroom most of the time?

- Yes
- No

Q38 In which grades do you teach? Select all that apply

☐ Elementary school (K-5)

☐ Middle school (6-8)

☐ High school (9-12)

Q39 On average, how many hours do you spend in classrooms every week?

- 10 or less
- 11 to 20
- 21 to 30
- 31 to 40
- 41 to 50
- 51 or more

Q40 On average, how many students do you have in your classes?

- 15 or less
- 16 to 20
- 21 to 25
- 26 to 30
- 31 to 35
- 36 or more

Q41 What gender do you identify with?

- Male
- Female
- Other_____
- Prefer not to say

Q42 What is your age?

- 18 to 24
- 25 to 34
- 35 to 44
- 45 to 54
- 55 or more

Q43 Is there anything you would like to add, that wasn't covered in the survey?

_____

Appendix C: IRB Approval

UNIVERSITY OF OREGON | Research Compliance Services

EXEMPT DETERMINATION

June 6, 2023

Maria Coronado Cabrera

mcorona6@uoregon.edu

Dear Maria Coronado Cabrera:

The following research was reviewed and determined to qualify for exemption.

Type of Review:	Initial Study
Study Title:	Comfort and Well-being in Classrooms
Principal Investigator:	Maria Coronado Cabrera
Parent Study ID:	STUDY00000912
Transaction ID:	STUDY00000912
Funding Source:	Name: University of Concepcion; Name: Ryoichi Sasakawa Young Leaders Fellowship Fund
Documents Reviewed:	• Application-exempt_determination, Category: IRB Protocol; • Category 2 worksheet, Category: IRB Protocol; • Funding and Sponsorship , Category: Sponsor Attachment; • Funding and Sponsorship , Category: Sponsor Attachment; • Informed consent Interview Facility Manager (ENG), Category: Consent Form; • Informed consent Interview Facility Manager (SP), Category: Consent Form; • Informed consent Interview Teacher (ENG), Category: Consent Form; • Informed consent Interview Teacher (SP), Category: Consent Form; • Informed consent Survey Qualtrics Teacher (ENG), Category: Consent Form; • Informed consent Survey Qualtrics Teacher (SP), Category: Consent Form; • Informed consent Survey Teacher (ENG), Category: Consent Form; • Informed consent Survey Teacher (SP), Category: Consent Form; • Teacher recruitment email, Category: Recruitment Materials; • Teacher recruitment email (SP), Category: Recruitment Materials;
Approval Date:	6/1/2023

Effective Date:	6/6/2023
Expiration Date:	5/31/2024

For this research, the following determinations have been made:

- This study has been reviewed under **the 2018 Common Rule** and determined to qualify for exemption under **Title 45 CFR 46.104(d) (2)(ii) Tests, surveys, interviews, or observation (low risk).**

For this research the following contingencies apply:

- Please note that since this research will be conducted in the countries of Chile and Columbia, this IRB approval is contingent upon obtaining authorization from human subject research review agencies in those countries if required by each country's human subject research policies. Documentation of authorization or confirmation that authorization is not required for this research should be obtained from a relevant ethics or regularly body or designee prior to beginning this research. Please keep a copy of that documentation for your records so it can be provided in event of an audit.
- This study involves conducting research in schools external to the University of Oregon. Please reach out to the schools and school districts to obtain approval as needed prior to conducting this research and maintain copies of those approvals so they can be supplied in the event of an audit. If any of the participating districts or schools has a formal research or ethics review process, documentation of their approval must be submitted to RCS as a modification to the study record prior to commencing this research.

The research is approved to be conducted as described in the approved protocol using the approved materials. Approved materials can be accessed in the protocol workspace in the IRB module of the research administration portal (RAP).

All changes to this research must be assessed to ensure the study continues to qualify for exemption. Research Compliance Services has developed specific guidance to help you understand when a modification is required before a change can be implemented. It is your responsibility to ensure modifications are submitted when required and approval secured before implementing changes to the protocol

Continuing Review is not required for this study. **An institutional approval period has been established based on your application materials.** If you anticipate the research will continue beyond the approval period, you must submit a **Continuing Review Application** at least 45 days prior to the expiration date. A closure report must be submitted once human subject research activities are complete. Failure to maintain current approval or properly close the protocol constitutes non-compliance.

With the submission of your request, you agreed to uphold the responsibilities of the Principal Investigator and have agreed to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB module of the RAP.

If you have any questions regarding your protocol or the review process, please contact Research Compliance Services at ResearchCompliance@uoregon.edu or (541)346-2510. The University of Oregon and Research Compliance Services appreciate your commitment to the ethical and responsible conduct of research with human subjects.

Please consider completing our user satisfaction survey. It only takes a few minutes, and we would like to hear about your experience working with our office!

Sincerely,

Research Compliance Services
on behalf of the Committee for Protection of Human Subjects

cc: Alison Kwok

References

Alameddine, I., Gebrael, K., Hanna, F., & El-Fadel, M. (2022). Quantifying indoor PM2.5 levels and its sources in schools: What role does location, chalk use, and socioeconomic equity play ? *Atmospheric Pollution Research*, *13*(4), 101375. https://doi.org/10.1016/j.apr.2022.101375

Allen, J., Spengler, J., Jones, E., & Cedeno-Laurent, J. (2020). *5-step guide to checking ventilation rates in classrooms*. www.ForHealth.org

Alonso, A., Llanos, J., Escandón, R., & Sendra, J. J. (2021). Effects of the COVID-19 Pandemic on Indoor Air Quality and Thermal Comfort of Primary Schools in Winter in a Mediterranean Climate. *Sustainability 2021, Vol. 13, Page 2699*, *13*(5), 2699. https://doi.org/10.3390/SU13052699

American Society of Civil Engineers (ASCE). (2021). *ASCE Schools 2021 report card*. https://infrastructurereportcard.org/cat-item/schools-infrastructure/

Andersson, K. (1998). *MM Questionnarie—FORM MM 040*. 38–41.

ASHRAE. (2017). ANSI/ASHRAE Standard 55-2017 Thermal environmental conditions for human occupancy. In *ANSI/ASHRAE Standard—55*. American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE).

ASHRAE. (2021). *2021 ASHRAE Handbook: Fundamentals*.

ASHRAE. (2022a). *ANSI/ASHRAE Standard 62.1—2022, Ventilation and Acceptable Indoor Air Quality*.

ASHRAE. (2022b). *ASHRAE Position Document on Carbon Dioxide*. 17.

ASHRAE. (2023a). *ANSI/ASHRAE Addendum ab to ANSI/ASHRAE Standard 62.1-2022*.

ASHRAE. (2023b). *ANSI/ASHRAE Standard 55-2023 Thermal environmental conditions for human occupancy*.

Bäfver, L. S., Leckner, B., Tullin, C., & Berntsen, M. (2011). Particle emissions from pellets stoves and modern and old-type wood stoves. *Biomass and Bioenergy*, *35*(8), 3648–3655. https://doi.org/10.1016/j.biombioe.2011.05.027

Baker, L., & Bernstein, H. (2012). The Impact of School Buildings on Student Achievement and Behavior. In *McGraw-Hill Research Foundation The Center for Green Schools*.

Bakó-Biró, Z., Clements-Croome, D. J., Kochhar, N., Awbi, H. B., & Williams, M. J. (2012). Ventilation rates in schools and pupils' performance. *Building and Environment*, *48*(1), 215–223. https://doi.org/10.1016/j.buildenv.2011.08.018

Batterman, S. (2017). Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms. *International Journal of Environmental Research and Public Health*, *14*(2). https://doi.org/10.3390/ijerph14020145

Batterman, S., Su, F. C., Wald, A., Watkins, F., Godwin, C., & Thun, G. (2017). Ventilation rates in recently constructed U.S. school classrooms. *Indoor Air*, *27*(5), 880–890. https://doi.org/10.1111/ina.12384

Bernardi, N. (2006). Environmental Comfort in School Buildings a Case Study of Awareness and Participation of Users. *ENVIRONMENT AND BEHAVIOR*, *38*(2), 155–172. https://doi.org/10.1177/0013916505275307

Betti, G., Tartarini, F., Nguyen, C., & Stefano, S. (2023). *Clima Tool: A free and open-source web application for climate analysis tailored to sustainable building design.* https://clima.cbe.berkeley.edu/

Brager, G. S., & de Dear, R. J. (2003). Historical and Cultural Influences on Comfort Expectations. In *Buildings, Culture and Environment* (pp. 177–201). Blackwell Publishing Ltd. https://doi.org/10.1002/9780470759066.ch11

Branco, P. T. B. S., Alvim-Ferraz, M. C. M., Martins, F. G., & Sousa, S. I. V. (2019). *Quantifying indoor air quality determinants in urban and rural nursery and primary schools*. https://doi.org/10.1016/j.envres.2019.108534

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P., & Kort, H. S. M. (2021). Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: A systematic literature review. *Indoor Air*, *31*(2), 405–425. https://doi.org/10.1111/ina.12745

Browning, M. H. E. M., & Rigolon, A. (2019). School green space and its impact on academic performance: A systematic literature review. *International Journal of Environmental Research and Public Health*, *16*(3). https://doi.org/10.3390/ijerph16030429

California Air Resources Board. (2003). *California Portable Classrooms Study. Phase II: Main Study*.

California Air Resources Board & California Department of Health Services. (2004). *Environmental Health Conditions in California Portable Classrooms*.

California Building Standards Commission. (2024). *2022 California Green Building Standards Code, Title 24, Part 11 (CALGreen) with July 2024 Supplement* (Version January 2023). https://codes.iccsafe.org/content/CAGBC2022P3/chapter-5-nonresidential-mandatory-measures

California Climate Adaptation Strategy. (n.d.). *Projected Climate Change Impacts on California*. Retrieved April 28, 2024, from https://climateresilience.ca.gov/overview/impacts.html

California Department of Education. (n.d.). *Federal Stimulus Funding*. Retrieved April 12, 2024, from https://www.cde.ca.gov/fg/cr/index.asp

California Department of Education. (2023). *School Accountability Report Card (SARC)*. https://sarconline.org/public/findASarc

California Department of Education. (2024). *Unduplicated Student Poverty – Free or Reduced-Price Meals Data 2023–24* [Dataset]. https://www.cde.ca.gov/ds/ad/filessp.asp

California Energy Commission. (2022). *Building Energy Efficiency Standards for Residential and Nonresidential Buildings. Title 24.*

Carvalho, R. L., Vicente, E. D., Tarelho, L. A. C., & Jensen, O. M. (2018). Wood stove combustion air retrofits: A low cost way to increase energy savings in dwellings. *Energy and Buildings*, *164*, 140–152. https://doi.org/10.1016/j.enbuild.2018.01.002

CDC. (2024, April 10). *Hierarchy of Controls*. Hierarchy of Controls. https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html

CDT. (2015). *Medición del consumo nacional de leña y otros combustibles sólidos derivados de la madera*.

Center for Green Schools. (2022). *School Facilities Funding in the Pandemic*.

Cerri, S., Maskrey, A., & Peppard, E. (2020). Retaining a healthy indoor environment in on-demand mixed-mode classrooms. *Developments in the Built Environment*, *4*, 100031. https://doi.org/10.1016/j.dibe.2020.100031

Chan, W. R., Li, X., Singer, B. C., Pistochini, T., Vernon, D., Outcault, S., Sanguinetti, A., & Modera, M. (2020). Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. *Building and Environment*, *167*(August 2019), 106426. https://doi.org/10.1016/j.buildenv.2019.106426

Cheeseman, M. J., Ford, B., Anenberg, S. C., Cooper, M. J., Fischer, E. V., Hammer, M. S., Magzamen, S., Martin, R. V., van Donkelaar, A., Volckens, J., & Pierce, J. R. (2022). Disparities in Air Pollutants Across Racial, Ethnic, and Poverty Groups at US Public Schools. *GeoHealth*, *6*(12). https://doi.org/10.1029/2022GH000672

Chen, J., & Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. *Environment International*, *143*(June), 105974. https://doi.org/10.1016/j.envint.2020.105974

Climate-Data. (n.d.). *Clima Concepción: Temperatura, Climograma y Tabla climática para Concepción*. Retrieved January 13, 2024, from https://es.climate-data.org/america-del-sur/chile/viii-region-del-biobio/concepcion-3984/

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003). Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. *Indoor Air*, *13*(1), 53–64. https://doi.org/10.1034/j.1600-0668.2003.00153.x

de Dear, R., Xiong, J., Kim, J., & Cao, B. (2020). A review of adaptive thermal comfort research since 1998. *Energy and Buildings*, *214*, 109893. https://doi.org/10.1016/j.enbuild.2020.109893

Du, B., Schwartz-Narbonne, H., Tandoc, M., Heffernan, E. M., Mack, M. L., & Siegel, J. A. (2022). The impact of emissions from an essential oil diffuser on cognitive performance. *Indoor Air*, *32*(1), 1–12. https://doi.org/10.1111/ina.12919

Durán-Narucki, V. (2008). School building condition, school attendance, and academic achievement in New York City public schools: A mediation model. *Journal of Environmental Psychology*, *28*(3), 278–286. https://doi.org/10.1016/j.jenvp.2008.02.008

Eitland, E. S. (2020). The Assessment of Building Interventions on Student Health. *ProQuest Dissertations and Theses*, 112.

EPA. (n.d.). *National Ambient Air Quality Standards (NAAQS) for PM*. Retrieved May 31, 2022, from https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

EPA. (2009). Indoor Air Quality Tools for Schools. Reference Guide. *Safe and Healthy School Environments*. https://doi.org/10.1093/acprof:oso/9780195179477.003.0010

Felmer Plominsky, G., Martínez Arias, A., Rivera, M. I., & Zepeda-Gil, C. (2023). Pobreza energética en contextos de exclusión urbana: Nuevos enfoques para la acción desde América Latina. *Revista INVI*, *38*(109), 1–16. https://doi.org/10.5354/0718-8358.2023.72446

Filardo, M., Vincent, J. M., & Sullivan, K. (2019). How crumbling school facilities perpetuate inequality. *Phi Delta Kappan*, *100*(8), 27–31. https://doi.org/10.1177/0031721719846885

Filardo, M., Vincent, J., Sung, P., & Stein, T. (2006). Growth and Disparity: A Decade of US Public School Construction. *Building Educational Success Together*, *October*, 1–40.

Fisk, W. J. (2017). The ventilation problem in schools: Literature review. *Indoor Air*, *27*(6), 1039–1051. https://doi.org/10.1111/ina.12403

Graham, L. T., Parkinson, T., & Schiavon, S. (2021). *Lessons learned from 20 years of CBE's occupant surveys* (1). *2*(1), Article 1. https://doi.org/10.5334/bc.76

Habil, M., & Taneja, A. (2011). Children's exposure to indoor particulate matter in naturally ventilated schools in India. *Indoor and Built Environment*, *20*(4), 430–448. https://doi.org/10.1177/1420326X11409455

Haverinen-Shaughnessy, U., & Shaughnessy, R. J. (2015). Effects of classroom ventilation rate and temperature on students' test scores. *PLoS ONE*, *10*(8), e0136165. https://doi.org/10.1371/journal.pone.0136165

Haverinen-Shaughnessy, U., Shaughnessy, R. J., Cole, E. C., Toyinbo, O., & Moschandreas, D. J. (2015). An assessment of indoor environmental quality in schools and its association with health and performance. *Building and Environment*, *93*(P1), 35–40. https://doi.org/10.1016/j.buildenv.2015.03.006

Hongyuan Jia. (2019). *Ggpsychro* [Computer software]. https://github.com/hongyuanjia/ggpsychro

IES-NCES. (2023). *School Pulse Panel: Responses to the pandemic and efforts toward recovery*. https://nces.ed.gov/surveys/spp/results.asp

International Well Institute, 21st Century School Fund, & National Council on School Facilities. (2021). *State of Our Schools 2021. America's PK-12 Public School Facilities*.

Korsavi, S. S., & Montazami, A. (2020). Children's thermal comfort and adaptive behaviours; UK primary schools during non-heating and heating seasons. *Energy and Buildings*, *214*, 109857. https://doi.org/10.1016/j.enbuild.2020.109857

Korsavi, S. S., Montazami, A., & Mumovic, D. (2020). Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors. *Building and Environment*, *181*. https://doi.org/10.1016/J.BUILDENV.2020.107061

Kwok, A. G. (1997). Thermal comfort in naturally-ventilated and air-conditioned classrooms in the tropics. In *UC Berkeley*. https://escholarship.org/uc/item/65d3k1jt

Li, D., & Sullivan, W. C. (2016). Impact of views to school landscapes on recovery from stress and mental fatigue. *Landscape and Urban Planning*, *148*, 149–158. https://doi.org/10.1016/j.landurbplan.2015.12.015

Lin, S., Lawrence, W. R., Lin, Z., Francois, M., Neamtiu, I. A., Lin, Q., Csobod, E., & Gurzau, E. S. (2017). Teacher respiratory health symptoms in relation to school and home environment. *International Archives of Occupational and Environmental Health*, *90*(8), 725–739. https://doi.org/10.1007/s00420-017-1235-x

Lin, S., Lipton, E., Lu, Y., & Kielb, C. (2020). Are classroom thermal conditions, lighting, and acoustics related to teacher health symptoms? *Indoor Air*, *30*(3), 544–552. https://doi.org/10.1111/ina.12640

Luther, M. B., Horan, P., & Tokede, O. (2018). Investigating CO_2 concentration and occupancy in school classrooms at different stages in their life cycle. *Architectural Science Review*, *61*(1–2), 83–95. https://doi.org/10.1080/00038628.2017.1416576

Marcotte, D. E. (2017). Something in the air? Air quality and children's educational outcomes. *Economics of Education Review*, *56*, 141–151. https://doi.org/10.1016/j.econedurev.2016.12.003

Maxwell, L. E. (2016). School building condition, social climate, student attendance and academic achievement: A mediation model. *Journal of Environmental Psychology*, *46*, 206–216. https://doi.org/10.1016/j.jenvp.2016.04.009

Mendell, M. J., Eliseeva, E. A., Davies, M. M., Spears, M., Lobscheid, A., Fisk, W. J., & Apte, M. G. (2013). Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air*, *23*(6), 515–528. https://doi.org/10.1111/ina.12042

Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air*, *15*(1), 27–52. https://doi.org/10.1111/j.1600-0668.2004.00320.x

Mendoza, D. L., Benney, T. M., & Boll, S. (2021). Long-term analysis of the relationships between indoor and outdoor fine particulate pollution: A case study using research grade sensors. *Science of The Total Environment*, *776*, 145778. https://doi.org/10.1016/J.SCITOTENV.2021.145778

Ministerio de Energia. (2021). *Acceso Equitativo a la Energia Sostenible. Politicas Publicas para combatir la Pobreza Energetica en Chile.*

Ministerio de Energia, BID, Centro de Inteligencia Territorial, & EBP. (2024). *Plataforma de Pobreza Energética*. Plataforma de Indicadores de Pobreza Energetica. https://vipe.minenergia.cl/

Ministerio de Medio Ambiente. (2011). *Decreto 12. Establece norma primaria de calidad ambiental para material particulado respirable MP2,5*.

Ministerio de Medio Ambiente. (2022). *Decreto 12. Establece norma primaria de calidad ambiental para material particulado respirable MP10*.

Ministerio del Medio Ambiente. (2019). *Decreto 6. Plan de prevención y de descontaminación atmosférica para las comunas de Concepción Metropolitano*.

Miranda, M. T., Romero, P., Valero-Amaro, V., Arranz, J. I., & Montero, I. (2022). Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with Mediterranean climate. *International Journal of Hygiene and Environmental Health*, *240*, 113910. https://doi.org/10.1016/J.IJHEH.2021.113910

Morakinyo, O. M., Mokgobu, M. I., Mukhola, M. S., & Hunter, R. P. (2016). Health outcomes of exposure to biological and chemical components of inhalable and respirable particulate matter. *International Journal of Environmental Research and Public Health*, *13*(6), 1–22. https://doi.org/10.3390/ijerph13060592

Park, J., Katz, L., Stavins, R., Shleifer, A., Heal, G., Chetty, R., Aldy, J., Goldin, C., Glaeser, E., Stock, J., Feldstein, M., Miron, J., Liebman, J., Mankiw, G., Keith, D., Goodman, J., Cutler, D., Auffhammer, M., Hsiang, S., & Reardon, S. (2016). Temperature, Test Scores, and Educational Attainment. *Harvard Economics Job Market Paper*, 166.

Park, R. J., Behrer, A. P., & Goodman, J. (2021). Learning is inhibited by heat exposure, both internationally and within the United States. *Nature Human Behaviour*, *5*(1), 19–27. https://doi.org/10.1038/s41562-020-00959-9

Pérez-Fargallo, A., Bienvenido-Huertas, D., Rubio-Bellido, C., & Trebilcock, M. (2020). Energy poverty risk mapping methodology considering the user's thermal adaptability: The case of Chile. *Energy for Sustainable Development*, *58*, 63–77. https://doi.org/10.1016/j.esd.2020.07.009

Persily, A. K. (2017). Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards. *NIST*, 810–819.

R Core Team. (2021). *R: A language and environment for statistical computing. R Foundation for Statistical Computing* [Computer software]. https://www.R-project.org/

Raysoni, A. U., Sarnat, J. A., Sarnat, S. E., Garcia, J. H., Holguin, F., Luvano, S. F., & Li, W. W. (2011). Binational school-based monitoring of traffic-related air pollutants in El Paso, Texas (USA) and Ciudad Juárez, Chihuahua (México). *Environmental Pollution*, *159*(10), 2476–2486. https://doi.org/10.1016/J.ENVPOL.2011.06.024

Reyes, R., Schueftan, A., Ruiz, C., & González, A. D. (2019). Controlling air pollution in a context of high energy poverty levels in southern Chile: Clean air but colder houses? *Energy Policy*, *124*, 301–311. https://doi.org/10.1016/j.enpol.2018.10.022

Riham Jaber, A., Dejan, M., & Marcella, U. (2017). The Effect of Indoor Temperature and CO2 Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia. *Energy Procedia*, *122*, 451–456. https://doi.org/10.1016/j.egypro.2017.07.378

Rissetto, R., Schweiker, M., & Wagner, A. (2021). Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort. *Energy and Buildings*, *235*, 110721. https://doi.org/10.1016/j.enbuild.2021.110721

Sadrizadeh, S., Yao, R., Yuan, F., Awbi, H., Bahnfleth, W., Bi, Y., Cao, G., Croitoru, C., de Dear, R., Haghighat, F., Kumar, P., Malayeri, M., Nasiri, F., Ruud, M., Sadeghian, P., Wargocki, P., Xiong, J., Yu, W., & Li, B. (2022). Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Journal of Building Engineering*, *57*. https://doi.org/10.1016/J.JOBE.2022.104908

Salthammer, T., Uhde, E., Schripp, T., Schieweck, A., Morawska, L., Mazaheri, M., Clifford, S., He, C., Buonanno, G., Querol, X., Viana, M., & Kumar, P. (2016). Children's well-being at schools: Impact of climatic conditions and air pollution. *Environment International*, *94*, 196–210. https://doi.org/10.1016/j.envint.2016.05.009

Schwartz-Narbonne, H., Du, B., & Siegel, J. A. (2021). Volatile organic compound and particulate matter emissions from an ultrasonic essential oil diffuser. *Indoor Air*, *31*(6), 1982–1992. https://doi.org/10.1111/ina.12845

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air*, *14*(5), 333–341. https://doi.org/10.1111/j.1600-0668.2004.00251.x

Simons, E., Hwang, S. A., Fitzgerald, E. F., Kielb, C., & Lin, S. (2010). The impact of school building conditions on student absenteeism in upstate New York. *American Journal of Public Health*, *100*(9), 1679–1686. https://doi.org/10.2105/AJPH.2009.165324

Singh, M. K., Ooka, R., Rijal, H. B., Kumar, S., Kumar, A., & Mahapatra, S. (2019). Progress in thermal comfort studies in classrooms over last 50 years and way forward. *Energy & Buildings*, 149–174. https://doi.org/10.1016/j.enbuild.2019.01.051

Tartarini, F., Schiavon, S., Cheung, T., & Hoyt, T. (2020). CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX*, *12*. https://doi.org/10.1016/j.softx.2020.100563

The Center for Green Schools & ASHRAE. (2021). *Preparation in the Pandemic: How Schools Implemented Air Quality Measures to Protect Occupants from COVID-19*.

The Center for Green Schools & ASHRAE. (2022). *Managing Air Quality During the Pandemic: How K-12 Schools Addressed Air Quality in the Second Year of COVID-19* (p. 46).

Toftum, J., Kjeldsen, B. U., Wargocki, P., Menå, H. R., Hansen, E. M. N., & Clausen, G. (2015). Association between classroom ventilation mode and learning outcome in Danish schools. *Building and Environment*, *92*, 494–503. https://doi.org/10.1016/j.buildenv.2015.05.017

Toyinbo, O., Shaughnessy, R., Turunen, M., Putus, T., Metsämuuronen, J., Kurnitski, J., & Haverinen-Shaughnessy, U. (2016). Building characteristics, indoor environmental quality, and mathematics achievement in Finnish elementary schools. *Building and Environment*, *104*, 114–121. https://doi.org/10.1016/j.buildenv.2016.04.030

Trebilcock, M., Soto-Muñoz, J., Yañez, M., & Figueroa-San Martin, R. (2017). The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. *Building and Environment*, *114*, 455–469. https://doi.org/10.1016/j.buildenv.2016.12.036

UNEP. (2017, November 16). *Chile takes action on air pollution*. UNEP. http://www.unep.org/news-and-stories/story/chile-takes-action-air-pollution

United States Environmental Protection Agency. (2018). Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI). *Environmental Protection*, 22.

U.S. Government Accountability Office. (2020). *K-12 Education: School Districts Frequently Identified Multiple Building Systems Needing Updates or Replacement* (Issue June, pp. 1–94). https://www.gao.gov/products/gao-20-494

Wargocki, P., & Wyon, D. (2007a). The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *HVAC and R Research*, *13*(2), 165–192.

Wargocki, P., & Wyon, D. P. (2007b). The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). *HVAC and R Research*, *13*(2), 193–220. https://doi.org/10.1080/10789669.2007.10390951

Wargocki, P., & Wyon, D. P. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment*, *59*, 581–589. https://doi.org/10.1016/j.buildenv.2012.10.007

Wargocki, P., & Wyon, D. P. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment*, *112*, 359–366. https://doi.org/10.1016/j.buildenv.2016.11.020

WHO. (2021). WHO global air quality guidelines. *Coastal And Estuarine Processes*, 1–360.

Yaneva, A. (2009). Making the Social Hold: Towards an Actor-Network Theory of Design. *Design and Culture*, *1*(3), 273–288. https://doi.org/10.1080/17547075.2009.11643291

Yaneva, A. (2022). *Latour for Architects: Thinkers for Architects* (1st ed.). Routledge. https://doi.org/10.4324/9780429328510

Yin, R. K. (2018). *Case study research and applications. Design and methods* (Sixth). SAGE Publications Inc.

Zhang, D., Ding, E., & Bluyssen, P. M. (2022). Guidance to assess ventilation performance of a classroom based on CO 2 monitoring. *Indoor and Built Environment*, *January*, 1420326X2110587. https://doi.org/10.1177/1420326x211058743

Zhang, F., & de Dear, R. (2019). Impacts of demographic, contextual and interaction effects on thermal sensation—Evidence from a global database. *Building and Environment*, *162*, 106286. https://doi.org/10.1016/j.buildenv.2019.106286