Optimised Indoor Air Quality and Thermal Comfort for Primary School Classrooms –

A New Zealand Case Study

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Dedication

This dissertation is dedicated to my ancestors and to the longing memory of my elder brother, whose unwavering support, guidance, devotion and wisdom have been a beacon of light throughout my life. Their presence may have left this world, but their holy spirit and influence remain deeply embedded within the pages of this academic work.

To my ever-supporting parents, guardians and other family members, who consistently offered their support and prayers.

A special tribute to the woman for my ultimate source of strength – My Mother. You have been my unwavering support, backbone, and most ardent believer from miles away. Your unconditional love has been a constant source of inspiration, transcending distance and time. Your dedication to my journey, your endless prayers, and your profound belief in my potential have been the invisible thread that has guided me through every challenge.

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Abstract

In the wake of the COVID-19 pandemic, the critical importance of indoor air quality (IAQ), thermal comfort (TC) and ventilation in school spaces has gained unprecedented relevance. This research, initiated in 2020 at Massey University, Auckland, New Zealand, strategically coincided with the global reconsideration of indoor environment norms and guidelines, providing a timely opportunity to establish comprehensive frameworks for evaluating school environments in New Zealand primary schools.

Schools function as second homes where children spend approximately 13,000 hours throughout their academic journey, with up to 90% of their developmental years in indoor educational environments. This extensive indoor exposure makes the quality of school environments particularly consequential for students' physical and mental development. Despite this significance, New Zealand primary schools predominantly rely on natural ventilation systems, often limited to manual window operation, raising concerns about consistent environmental quality maintenance, which often raises concerns about poor IAQ and TC presence within the indoor environment.

While the Ministry of Education (2022), has established the Designing Quality Learning Spaces (DQLS) document as a framework for school design standards, significant gaps remain between these guidelines and the practical reality in many classrooms. The current DQLS guidelines provide minimum mandatory requirements for IAQ and TC, tailored to New Zealand's diverse climate zones. Furthermore, the COVID-19 pandemic has highlighted additional ventilation needs for reducing viral transmission risks that have not been fully addressed in existing DQLS versions. This research investigates these shortcomings in the current DQLS framework.

This study employs a multi-stage methodology using a mixed-method approach. First, it compares the evolution of Designing Quality Learning Spaces (DQLS) guidelines from version 1.0 (2017) to version 2.0 (2022), establishing the current regulatory context. Second, it conducts content and document analyses comparing DQLS v2.0 with international benchmarks, including WHO, ASHRAE 62.1, CIBSE TM 57, EN-15251, and Building Bulletins 99 and 101. Third, it performs detailed simulation studies across six diverse climate zones of New Zealand using two representative primary school typologies, namely Avalon Block and Canterbury Block, examining multiple parameters, including temperature, relative humidity, ventilation rates, carbon dioxide levels, window-to-wall ratios, occupant density, classroom dimensions, and ventilation strategies. Finally, it incorporates industrial validation with experts in school designing, architects, building scientists, and facility managers through qualitative and quantitative analyses via open-ended and Likert scale questionnaires for findings and design changes to develop optimal IAQ and TC guidelines for New Zealand primary school classrooms for the post-COVID-19 environment.

The research addresses critical gaps for New Zealand primary schools, where high occupancy density, infrequent facility inspections, and simple ventilation mechanisms create vulnerable conditions, especially in the post-pandemic context when extended school closures created conditions potentially favourable for the accumulation of indoor pollutants while simultaneously increasing awareness about transmission risks.

By connecting established knowledge about IAQ and TC impacts with the new pandemic context, this research provides timely insights for educational facility management, public health policy, and pedagogical practice in ensuring optimal learning environments for students, teachers, and caregivers during their most formative years. This work contributes significantly to understanding how learning environments can be designed to support health and educational outcomes in a world transformed by pandemic awareness.

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Abbreviations and Acronyms

ACH	Air Change per Hour
ACP	Adaptive Comfort Percentage
AHPPC	Australian Health Protection Principal Committee
AMV	Adaptive Mean Vote
aPMV	Adaptive Predictive Mean Vote
AQG	Air Quality Guidelines
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BB	Building Bulletin
BPA	Building Performance Assessment
BRANZ	Building Research Association of New Zealand
cDA	Continuous Daylight
CDC	Centres for Disease Control
CIBSE	Charted Institution for Building Services Engineers
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease 2019
CSP	Cooling Sensation Percentage
CZ	Climate Zones
DA	Daylight
DQLS	Designing Quality Learning Spaces
ECDC	European Centre for Disease Prevention and Control
EN	European Nation
EPW	Energy Plus Weather
EU	European Union

FLS	Flexible Learning Spaces
GAS	Group A Streptococcal
GBDR	The Global Burden of Disease Risk
GH	Grasshopper
HBT	Honeybee Tools
HSP	Heating Sensation Percentage
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ISO	International Standardization of Organisations
kWh/m^2	kilo Watt hour per meter square
LBT	Ladybug Tools
LSP	Litre per second per person
m^2	meter square
MCO	multi-criteria Optimisation
MOE	Ministry of Education
NCEA	National Certificate of Educational Achievement
NIWA	National Institute of Water and Atmospheric Research
NV	Natural Ventilation
NZ	New Zealand
NZIA	New Zealand Institute of Architects
NZIOB	The NZ Institute of Building
NZS	New Zealand Standards
OECD	Organisation for Economic Cooperation and Development
PM	Particulate Matters
PMV	Predicted Mean Vote

POEs	Post Occupancy Evaluations
PPD	Predicted Percentage of Discomfort
PPM	parts per million
REHVA	The Federation of European Heating, Ventilation and Air Conditioning Associations
RH	Relative Humidity
RSV	Respiratory Syncytial Virus
SINPHONIE	Schools Indoor Pollution and Health Observatory Network in Europe
TC	Thermal Comfort
TCP	Thermal Comfort Percentage
TTI	Test, Trace and Isolate
UDI	Useful Daylight Illuminance
UNESCO	United Nations Educational, Scientific and Cultural Organization
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WWR	Window-to-Wall Ratio

List of Peer-reviewed Publications

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1. Introduction

1.1 Area of Research

Indoor Environmental Quality (IEQ) in school premises encompasses the comprehensive conditions within a building that affect occupant comfort, health, and well-being. This multifaceted concept is influenced by numerous factors, including external environmental conditions (such as ambient pollution and temperature), building materials, orientation, furnishing, ventilation systems (mechanical and natural), and human activities like system operation and maintenance (Almeida et al., 2015). Hence, the evaluation of IEQ in early building design and construction is considered a very crucial factor (Fathi & O'Brien, 2023). IEQ is identified with four principal components that significantly impact building occupants' health outcomes: lighting quality, thermal conditions, acoustics, and air quality (Catalina & Iordache, 2012). The prominence of these principles stems from their fundamental relationship to visual perception, sound management, temperature regulation, and the energy-efficient design principles of constructed environments (Aturupane et al., 2013; Barrett & Zhang, 2009). The above four principles in school premises warrant particular attention regarding these environmental factors, as classroom conditions directly influence students' cognitive function, attention span, and educational engagement (Pellegrino et al., 2015). Corresponding to Andamon et al., (2019), students spend up to 90% of their developmental years indoors at school, accumulating roughly 13,000 hours throughout their academic journey from preschool to Standard 12. Within New Zealand, children accumulate approximately 900 hours annually in school buildings. Throughout their complete educational trajectory (years 1-13), students spend roughly 11,700 hours within school premises, constituting approximately 15% of their conscious existence(Ackley, 2021). Given this substantial temporal investment, the quality of indoor environments in educational settings remains a persistent focus for researchers, educational stakeholders, and parental communities (Bennett et al., 2019; Yassin & Pillai, 2019).

Research concerning indoor environmental conditions within school premises constitutes a significant focus internationally (Andamon et al., 2019). The popularity of IEQ studies in school premises stems primarily from two critical considerations: classroom spaces typically contain a high number of young occupants who experience prolonged exposure to contaminants originating from various internal and external sources (Chithra & Nagendra, 2018). Additionally, educational infrastructure frequently receives inadequate maintenance oversight and sustainability assessment, which often exhibit high rates of viral transmission and illness among students resulting in documented substandard IEQ conditions in school spaces across different geographical contexts. The intersection of vulnerable populations and the prevalence of health issues directly attributable to poor indoor environmental quality creates compelling justification for continued scholarly examination of this domain.

Research demonstrates that classroom IEQ significantly influences educational outcomes, either enhancing or impeding learning performance. These findings remain consistent even when researchers account for confounding variables, including students' socioeconomic background, attendance patterns, educational level, and potential teacher evaluation biases (Ackley, 2021). The scholarly literature addresses distinct principles of IEQ through various investigative approaches. For Example, visual comfort, primarily characterised by daylight availability and exterior view quality, has been examined in multiple studies (Chen et al., 2018; Qingsong & Fukuda, 2016). Thermal comfort optimisation, considering architectural elements such as fenestration, spatial configuration, and shading devices, has been explored by several researchers (Elghamry & Hassan, 2020; Zhao & Du, 2020). Acoustic environmental quality has received attention in numerous investigations (Badino et al., 2019;

Eltaweel & Yuehong, 2017), while air quality considerations have been addressed in other research efforts (Diaz et al., 2021; Korsavi et al., 2020; Mabdeh et al., 2020; Temprano et al., 2020).

In the year 2020, the SARS-CoV-2 pandemic catalysed heightened scrutiny of suboptimal IEQ within school spaces, elevating this concern above traditional comfort parameters. Epidemiological research has established respiratory aerosols as a significant vector for viral transmission, with transmission risk substantially amplified in densely populated indoor settings such as classrooms (Alonso et al., 2021). This scientific understanding has prompted regulatory bodies worldwide to implement revised protocols specifically for educational institutions, with particular emphasis on optimising natural ventilation strategies. In New Zealand, approximately 90% of school classrooms rely on natural ventilation as the main source of airflow through windows and doors manual operations (Trompetter et al., 2018).

This widespread reliance on natural ventilation systems gained unprecedented attention during the COVID-19 pandemic when classrooms with historically suboptimal IEQ conditions required urgent reconsideration. The established scientific connection between airborne viral transmission and inadequate ventilation necessitated significant increases in fresh air intake and air exchange rates to create healthier learning environments.

For instance, the global concern regarding airborne transmission in educational settings spurred New Zealand's Ministry of Education to update its school design guidelines comprehensively (Ministry of Education, 2022). These revisions aimed to mitigate potential viral transmission through improved ventilation strategies and deliver educational spaces that effectively support diverse teaching methodologies and learning activities. The updated guidelines represent a shift from viewing ventilation solely as a technical building requirement to recognising it as an essential component of the pedagogical infrastructure. This holistic approach acknowledges that optimal air quality contributes significantly to student cognitive function, engagement, and overall well-being, factors crucial for effective education delivery. The NZ Ministry's response reflects a growing international consensus that school environmental quality requires strategic investment to address immediate health concerns and long-term educational outcomes, particularly in systems predominantly reliant on natural ventilation strategies.

The heightened requirements to tackle the challenging IEQ conditions represent a paradigm shift in building operation priorities, where infection risk mitigation through passive airflow techniques now supersedes energy conservation and thermal comfort considerations that previously dominated facility management practices (Stabile et al., 2021). However, implementing window-based ventilation and other natural airflow solutions presents particular challenges for school spaces in varied climate zones, where increased outdoor air exchange may conflict with thermal regulation demands, creating complex design trade-offs between health protection, occupant comfort and learning ability. Additionally, these interventions must account for diverse architectural configurations, window placement, and building orientations, volume & occupant density, and design envelopes that characterise the educational infrastructure in many regions (Aguilar et al., 2021).

As such, design interventions must be assessed in multi-criteria optimisation rather than isolation to comprehensively understand classroom environments (Pistore et al., 2020). This integrated approach allows researchers to identify interactive effects between different IEQ domains and develop comprehensive strategies that optimise overall environmental quality. A multidimensional assessment framework enables a more nuanced understanding of how various environmental factors collectively influence educational settings and learning outcomes. Hence, this study was shaped into a case study of primary school classrooms in New Zealand to examine IEQ design and management based on the Designing Quality Learning Spaces (DQLS) document published under the New Zealand Ministry of Education. The purpose was to evaluate the performance of New Zealand primary school classrooms with context to COVID-19, a global concern.

1.2 COVID-19: Impact in School Spaces (When, How & What)

The declaration of COVID-19 as a global health emergency by the World Health Organization on March 11, 2020, encouraged a renewed academic focus on the substandard IEQ in educational buildings worldwide, particularly regarding air circulation and thermal regulation. This increased awareness fundamentally re-evaluated building design strategies for ventilation in learning spaces. Accumulating evidence indicates that the transmission of COVID-19 is significantly influenced by air movement and suboptimal indoor environmental conditions. As scientific research identified aerosolised particles as a primary mode of the previous SARS-CoV-2 transmission, the virus responsible for COVID-19 (Organization, 2020). It suggested a significant risk of airborne viral spread in confined spaces such as school classrooms (Noorimotlagh et al., 2021). Hence, in March 2020, educational spaces across more than 180 nations experienced an unprecedented disruption, with approximately 1.6 billion students, from primary school children to university-aged young adults, no longer participating in formal on-site education (Panovska-Griffiths et al., 2020),. This global cessation of traditional schooling represented an educational discontinuity of historical proportions, affecting learners across diverse geographic regions and educational systems worldwide.

To curb viral transmission, educational spaces worldwide began closing in March 2020. However, these preventive measures adversely affected academic continuity, social development, psychological stability, and overall mental health (Stage et al., 2020). While educational space closures effectively reduced interpersonal interactions among populations, and curtailed disease transmission; such measures simultaneously generated substantial adverse consequences. These negative outcomes encompass impaired workforce availability in essential sectors, particularly healthcare, diminished economic output, and detrimental effects on young people's educational trajectories and well-being. The latter includes compromised developmental progress and deterioration in both physiological and psychological health states among children and adolescents, stemming from reduced social connectivity, decreased access to support networks, and potentially heightened vulnerability to domestic violence. These multifaceted repercussions highlight the complex cost-benefit considerations inherent in implementing such public health interventions (Macartney et al., 2020; Panovska-Griffiths et al., 2020; Viner et al., 2020).

While still applicable in recent times, such educational disruption manifested in the heightened academic burden on students who struggled to comprehend curriculum material delivered through remote instructional modalities. This challenge was compounded by inequitable access to technological resources, as many young learners lacked the dedicated electronic devices necessary for effective participation. Consequently, fundamental pedagogical sessions were frequently missed, compromising the acquisition of essential learning competencies. Furthermore, certain academic disciplines proved particularly resistant to effective remote instruction methodologies. These educational deficits placed numerous students at risk of academic year repetition. The suspension of traditional assessment mechanisms necessitated alternative evaluation approaches based on subjective criteria, while learners requiring specialised educational interventions experienced significant losses in targeted academic support services (Weale & Batty, 2020). Subsequent research purported that the resumption of in-person schooling did not lead to major outbreaks or increased transmission (Bonell et al., 2020; Public Health England, 2020). Nevertheless, some studies emphasised that the return to classrooms must be accompanied by robust Test, Trace, and Isolate (TTI) procedures to prevent subsequent infection surges (Panovska-Griffiths et al., 2020). Scientific findings and international guidelines for reopening educational facilities (Jones et al., 2020) highlighted the need for multifaceted mitigation strategies. These include physical distancing (minimum 2-meter separation), face coverings, improved hygiene practices, temperature screening, and optimised air exchange systems (Noorimotlagh et al., 2021; Stage et al., 2020; Tang et al., 2020).

The educational settings can operate safely and effectively using appropriate ventilation systems. Empirical data suggests that natural ventilation methods, when properly implemented, can successfully expel contaminated indoor air and introduce fresh outdoor air (Bonell et al., 2020). When natural ventilation alone is insufficient, hybrid systems that combine natural and mechanical ventilation approaches may provide enhanced air quality control. Ventilation strategies, potentially supplemented by filtration technologies, are key interventions for controlling infectious diseases and reducing transmission risks (Buonanno et al., 2020; Dietz et al., 2020; Morawska & Cao, 2020). However, significant differences exist between ventilation types as systems that utilise centralised air distribution or recirculation may create conditions favourable to the rapid spread of pathogens (Lipinski et al., 2020). Thus, it is necessary to keep and maintain a healthy environment to ensure safety and minimise transmission in a post-COVID-19 scenario where classrooms offer a conducive IEQ and best practices by international standards.

1.3 Post-COVID-19: IEQ Expectations of School Classroom

Effective monitoring of environmental parameters including air temperature, relative humidity, ventilation rate & carbon dioxide levels alongside complementary interventions, is crucial for maintaining acceptable indoor conditions in educational settings (Stage et al., 2020).

As school attendance represents a fundamental activity for developing children and students, evaluating thermal comfort and air quality in classrooms becomes particularly important (Almeida & De Freitas, 2014; Teli et al., 2013; Toftum et al., 2015). The COVID-19 pandemic highlighted the social significance of IEQ in educational spaces, despite numerous research studies documenting inadequate conditions in school buildings prior to the pandemic.

Research on indoor air quality (IAQ) and ventilation in Australian school classrooms remains critically limited, with substantial knowledge gaps particularly evident in the Australian and New Zealand context (Andamon et al., 2023). Pre-pandemic research in Australia had already identified systemic ventilation inadequacies across diverse climate zones. In subtropical Brisbane, median CO_2 concentrations of 1000 ppm were found in 50 naturally ventilated classrooms (Laiman et al., 2014). However, air change rates declined notably during colder periods compared to warmer periods, indicating inadequate seasonal ventilation, though corresponding ventilation rates per person were not reported. More concerning conditions emerged in temperate regions, with documented CO_2 concentrations ranging from 442 to 1,510 ppm in autumn and 718 to 2,114 ppm in winter in Sydney classrooms, with maximum levels exceeding 2,900 ppm (Haddad et al., 2019). In regional Victoria, Luther et al. (2018), reported CO_2 levels surpassing 2,700 ppm. The most comprehensive Victorian study revealed that median CO_2 concentrations exceeded 1,000 ppm in 70% of monitored classrooms (Andamon et al., 2023). The estimated ventilation rates of 4.08 L/s per person were 35-40% below the Australian requirement of 10-12 L/s per person, and air change rates were significantly lower than the WHO's recommended 6 ACH (Andamon et al., 2023; WHO, 2021).

Given the potential negative consequences of poor IEQ on children's populations, researchers have increasingly focused on analysing natural ventilation strategies and their impact on classroom conditions (Brelih & Seppänen, 2011). Indoor air quality has gained prominence due to its documented effects on occupant health and well-being. Maintaining acceptable air quality presents particular challenges in densely populated educational environments where occupants typically spend extended periods daily (Camacho-Montano et al., 2019; Wargocki et al., 2002).

The COVID-19 pandemic has necessitated modifications to occupant behaviours and ventilation practices. Indoor air quality and carbon dioxide levels have received heightened attention as educational spaces were identified as potential transmission zones for SARS-CoV-2. Since the virus primarily spreads through airborne particles released during breathing, speaking, coughing, or sneezing, managing classroom air quality became critical. Also, the pandemic has transformed perspectives on building engineering regarding health considerations and emphasised ventilation importance. Returning to in-person education required implementing protective measures for students and educators (Gil-Baez et al., 2021; Greenhalgh et al., 2021). While appropriate natural ventilation strategies can effectively reduce carbon dioxide levels, they simultaneously affect other environmental parameters, including thermal comfort and IAQ. These factors directly influence student learning performance and capacity. Research links IEQ factors to academic achievement, illness prevalence, and attendance rates (Aguilar et al., 2021; Daisey et al., 2003; Heracleous & Michael, 2018).

Studies conducted during the pandemic examined natural ventilation protocols in classrooms across various climate regions. Recommendations from studies suggested ventilation rates of at least 12.5 litres per second per person (l/s/p) in educational spaces(Hänninen & Haverinen-Shaugnessy, 2015; Moreno Grau et al., 2020). Recent research emphasizes that inadequate ventilation contributes to transmitting airborne diseases, with higher-occupancy spaces like classrooms being particularly vulnerable. Studies have established correlations between ventilation rates and disease transmission percentages (Bhagat et al., 2020; Melgar et al., 2021).

To maintain transmission rates below 1% in confined spaces, experts recommend maintaining 7 Air Changes per Hour (ACH) during continuous teaching periods (Dai & Zhao, 2020). Natural ventilation offers a cost-effective solution that balances thermal comfort with healthy air quality while reducing airborne pathogen transmission (Andrade et al., 2018; Sun & Zhai, 2020). However, managing thermal conditions during colder months presents additional challenges when relying on natural ventilation. This challenge is particularly acute in Australian schools, where pre-pandemic Victorian classrooms showed median average temperatures of 19-22°C with relative humidity of 50-59% during school hours. While meeting Victorian thermal requirements (no cooling below 26°C, no heating above 18°C), these conditions revealed a fundamental design conflict: maintaining thermal comfort often necessitates closing windows during extreme weather, thereby compromising ventilation. Australian schools predominantly rely on natural ventilation without mechanical outdoor air supply, with split air conditioning units installed for cooling, typically providing no ventilation (Andamon et al., 2023). The National Construction Code (2019) requires classroom window areas to constitute 12.5% of the floor area, based on a minimum of 2 m² per student; however, it provides no requirements regarding when, how much, or how often windows should be opened.

The Chartered Institution of Building Services Engineers (CIBSE) (2021) suggests circulating more fresh air cycles to achieve healthy indoor air quality, especially during colder weather. Recommendations from CIBSE (2021) include purging spaces, increasing window opening cycles, and prioritising clerestory openings in colder conditions. Sustaining air exchange at 5-6 air changes hourly represents a critical threshold, achievable through strategic partial deployment of windows and doorways. Upper-level fenestration benefits ventilation while minimising uncomfortable air currents and alternating between intensive ventilation periods and heating cycles to maintain atmospheric and thermal equilibrium. The Australian Health Protection Principal Committee (2021) corroborates these approaches, underscoring the necessity of optimising classroom air circulation through strategic aperture management. The Victorian school operation guidance recommends opening windows and doors to maximise ventilation while simultaneously operating heating and air conditioning systems an energy-intensive approach that overlooks integrated design addressing energy efficiency, IAQ, health, and comfort (VSBA and DET, 2022). Existing ventilation standards, which suggest up to six ACH for classrooms and an RH of (40–60%), are considered by numerous researchers to be insufficient during pandemic situations. The prevailing consensus indicates a need to reassess and potentially augment these recommended ventilation rates to mitigate pathogen transmission in enclosed educational spaces effectively (Dietz et al., 2020; Domínguez-Amarillo et al., 2020; Jones et al., 2020).

Health organisations recommend increasing fresh air circulation, particularly during adverse weather conditions. Strategies include purging spaces, implementing window opening cycles, and utilising clerestory openings to minimise drafts. A combination of purging and heating cycles can maintain air quality and thermal comfort. The WHO (World Health Organization, 2021a) recommends 10 litres per second per person of outdoor air for healthy indoor conditions. Research by (Papadopoulos et al., 2023) indicates that educational spaces require approximately 4 m² of fenestration area to achieve ventilation rates of 9-10 L/s per occupant during warmer months, while approximately half this area suffices during colder periods when supplementary heating is employed. In the aftermath of the pandemic, academic and physiological benefits correlate with maintaining carbon dioxide concentrations between 800-900 parts per million (REHVA, 2020; WHO, 2021a; CIBSE, 2021), with concentrations at or below 900 ppm showing marked enhancement in student cognitive function (Wargocki et al., 2017; Kuramochi et al., 2023). However, Australian pre-pandemic data demonstrated that all monitored Victorian classrooms, with more than 70% exceeding 1,000 ppm, indicated systemic failures in achieving these targets through natural ventilation alone (Andamon et al., 2023). Investigations into the relationship between ventilation parameters and intellectual performance reveal that elevating air exchange from 15 to 25 L/s/p per individual corresponds with a 10% improvement in cognitive capabilities (Kuramochi et al., 2023).

Pandemic protocols for classrooms typically included opening all windows and doors one hour before class sessions, maintaining this configuration throughout teaching activities, and continuing ventilation for one hour after activities concluded. Even during adverse weather conditions, natural ventilation through open windows and doors was mandated (Aguilar et al., 2021).

Spaces with higher occupancy require specific mitigation techniques to improve indoor air quality. Strategic approaches include increasing outdoor air supply and cleaning air circulation to reduce viral concentrations. Increased fresh air addresses viral presence and reduces volatile organic compounds. Additional measures include ultraviolet treatment to sterilise air, enhanced cleaning protocols for floor surfaces, and maintaining humidity levels between 40-60% to minimise viral transmission and reduce particulate matter concentrations (Environmental Protection Agency, 2020; Perkins and Will, 2020; Harvard T.H. Chan, 2020). In response to the pandemic, a demand-controlled ventilation (DCV) intervention in Sydney classrooms reduced peak CO_2 concentrations from 2,981 ppm to 1,335 ppm, yet this mechanical solution remains economically unfeasible for widespread implementation across Australian schools (Haddad et al., 2021). This intervention paradoxically demonstrates both the severity of IAQ problems and the imperative to develop effective natural ventilation strategies. Hence, the majority of Australian schools (VSBA and DET, 2022) and New Zealand schools (Arya et al., 2024) rely on natural ventilation. Thus, it becomes prominent to adopt strategic interventions while optimising classroom design and window operations to achieve comparable CO_2 reductions.

1.4 Problem Statement

Scholarly attention has been directed toward indoor air quality (IAQ) and thermal Comfort (TC) in educational settings for numerous decades, as it constitutes a fundamental determinant of health outcomes and educational efficacy among juvenile and adult populations. Suboptimal IAQ and TC correlate with elevated rates of non-attendance, diminished academic achievement, compromised cognitive function, and heightened prevalence of persistent health conditions, including asthmatic and respiratory disorders. Classroom overcrowding combined with insufficient air exchange mechanisms results in elevated carbon dioxide concentrations, excessive thermal output from occupants, olfactory discomfort, and accumulation of harmful airborne contaminants, collectively degrading indoor air quality and thermal comfort.

New Zealand exhibits particularly concerning statistics regarding asthmatic conditions and severe allergic manifestations among students and adult populations (Murphy et al., 2023). During developmental stages, children's physiological systems require proportionally greater respiratory exchange. Research by Faustman et al., (2000) and Suk et al., (2003) demonstrate that paediatric populations exhibit increased vulnerability to airborne particulates due to accelerated metabolic processes and underdeveloped physiological defence mechanisms against environmental toxicants. Beyond immediate comfort considerations, inadequate IAQ and TC impact learning capacities and contribute to respiratory pathologies, with asthma a particularly prevalent condition among school-aged children (Norbäck & Nordström, 2008; World Health Organization, 2010). Children's physical stature positions them closer to ground-level air, increasing their exposure to settled airborne toxicants that concentrate at lower elevations (Etzel, 2007). Consequently, rising respiratory morbidity among small-aged populations has catalysed intensified research interest regarding IAQ and TC in educational environments. Escalating asthma prevalence and health complications among school-aged children demonstrate significant associations with inadequate ventilation infrastructure in educational facilities (Daisey et al., 2003; Mendell & Heath, 2005).

The predominant ventilation methodology in New Zealand primary educational institutions relies on passive natural mechanisms through manual window operation. This creates substantial challenges for maintaining adequate air exchange in densely populated environments, presenting particular challenges for achieving appropriate ventilation metrics and environmental quality standards (McIntosh, 2011).

Insufficient ventilation in educational environments represents a significant public health concern. Carbon dioxide concentration serves as a surrogate indicator for assessing classroom air exchange adequacy (Boulic et al., 2022). Approximately 90% of New Zealand classrooms utilise natural ventilation through operable windows, with ventilation effectiveness contingent upon teacher initiative. Survey data indicates that fewer than 50% of class teachers utilise window ventilation during instructional periods (Wang, 2020). Suboptimal ventilation metrics, particularly prevalent during winter months in New Zealand educational facilities, potentially compromise respiratory health outcomes (Smedje & Norbäck, 2000; Wang, 2020). Attendance patterns may facilitate elevated pathogen transmission during infectious disease outbreaks (Mendell et al., 2013; Morawska et al., 2020).

Research indicates that appropriately designed, maintained, and operated mechanical ventilation systems achieve satisfactory air exchange rates in educational environments (Gao et al., 2014). However, such systems entail substantial capital investment, energy consumption, and maintenance requirements (Angelon-Gaetz et al., 2015). Financial constraints, particularly following the 2010 implementation of energy expenditure limitations, render mechanical systems economically unfeasible for numerous New Zealand educational institutions, necessitating the development of alternative, cost-effective methodologies to enhance winter ventilation performance in primary schools (Boulic et al., 2022). New Zealand schools rely on natural ventilation, which leads to higher levels of CO_2. Research by McIntosh, (2011) evidenced an average CO_2 level exceeding ~1000 ppm in 37 per cent of classrooms for most of the day while operational in New Zealand schools. Similarly, another study by Cutler-Welsh, (2006) identified CO_2 levels exceeding ~1000 ppm for approximately 80 % of the day in 3 school classrooms in Christchurch, New Zealand. The collective research evidence demonstrates that naturally ventilated school spaces consistently exceed recommended carbon dioxide thresholds (typically ~1000 ppm).

COVID-19 infection rates in New Zealand reached their peak in March 2022, with transmission remaining high throughout the academic year. The NZ Ministry of Health epidemiological statistical data revealed that educators (41%) and childcare workers (38%) experienced the highest infection rates among occupational categories (Ministry of Health, 2022). At the same time, concurrent risks of measles resurgence and other outbreak scenarios remained elevated, as well as rheumatic fever. The encounter with the COVID-19 virus outbreak and one of the high infection rates in school spaces indicate an alarming situation for New Zealand's strategy against future epidemic readiness. Hence, integrated and robust strategic interventions and protocols in school spaces are required to minimise the potential to become a rapid transmitter of serious infectious diseases in future (Kvalsvig et al., 2023).

To minimise the spread of the COVID-19 virus, several governing bodies worldwide issued guidelines and protocols that all connect with keeping the indoor environment clean, allowing more fresh air circulation for a healthy and optimal environment. Section 1.3 discusses certain norms and protocols issued by WHO, CIBSE, EPA, Harvard T.H. Chan, AHPPC, and interventional studies in COVID-19 and the indoor environment. The governing body of New Zealand, the Ministry of Education, holds an extensive portfolio encompassing over 15,000 buildings and 35,000 teaching spaces across approximately 2,100 schools. In 2022, the Ministry acted alongside international protocols and guidelines to upgrade the IAQ, TC, and Ventilation minimum mandatory and recommendations for New Zealand school buildings and developed a DQLS version 2.0 document (Ministry of Education, 2022).

Considering the history of New Zealand school buildings, there is a gap in knowledge regarding the efficacy of the NZ IAQ and TC guidelines and relative comparisons with international standards for optimal indoor environments. This ascertains that the appropriate design measures are in place to minimise the transmission of viral illness to the present time and for future pandemics. In section 1.5, the study explores the COVID-19 impact on New Zealand primary schools and its relative effect on children's attendance, academic achievement, behavioural issues, socio-economic disparities, and concerns with educators with extra workloads. The section discusses the transmission of disease in New Zealand and worldwide school spaces, the total number of cases, and critical health conditions to post infections. Section 1.6 discusses the importance of designing the built environment (schools for this study) for post-COVID-19 with context to enhanced indoor environment parameters (IAQ, TC, Ventilation system, RH) can help with recovery of viral transmission and how it can shape toward better future endeavours to support healthy living for both children and adults.

1.5 COVID-19: Impact on New Zealand School Education

The COVID-19 pandemic precipitated substantial disruptions within the educational systems of New Zealand, manifesting in several concerning trends. Data indicate a dramatic decline in consistent attendance patterns, with regular attendance metrics falling to approximately 40% during the second term of 2022 due to illness and isolation requirements. Despite partial recovery to 51% by the year's end, this pattern brought about enduring consequences beyond the immediate health crisis (Ministry of Education, 2024).

Behavioural issues in school children persisted as a significant concern within educational environments during the pandemic. Approximately 41% of school administrators reported behavioural challenges exceeding typical expectations for comparable periods in the year 2023 (Education Evaluation Centre, 2023), a figure statistically consistent with 2021 observations (39%). However, academic concerns had intensified considerably, with 43% of principals expressing apprehension regarding learning outcomes, substantially increasing from 27% in the previous year (2020). Notable is the finding that 26% of principals indicated their struggling students demonstrate achievement gaps of two or more curriculum levels (Education Evaluation Centre, 2023). Literacy development, particularly writing proficiency, emerged as the predominant concern among educational professionals, with 51% of principals and 44% of teachers identifying it as their primary academic concern. Concurrently, qualification attainment measured by NCEA Level 2 deteriorated relative to pre-pandemic (2019) benchmarks (NZQA, 2022).

Socioeconomic disparities were evident in these educational impacts. Schools serving socioeconomically disadvantaged communities reported significantly higher rates of concern regarding student progress (53%) than those in more affluent areas (31%) (Education Evaluation Centre, 2023). This disparity extended to achievement gaps, with principals in lower-income communities being over three times more likely to report struggling learners falling behind by two or more curriculum levels (46% versus 14%). NCEA Level 2 attainment differences between socioeconomic groups expanded from 14.5 percentage points in 2019 to 17.8 percentage points in 2022 (Ministry of Education, 2024).

The 2022-2023 period witnessed continued disruption to educational operations nationwide as institutions adapted to widespread community transmission. Peak viral transmission occurred in March 2022, maintaining elevated levels throughout the academic year. The NZ Ministry of Health epidemiological data revealed that educators (41%) and childcare workers (38%) experienced the highest infection rates among occupational categories (Ministry of Health, 2022). This likely contributed to the sharp decline in regular attendance, which is defined as attending more than 90% of half-days from approximately 60% in Term 2 of 2021 to merely 40% during the corresponding period in 2022 (Education Counts, 2025).

1.5.1 Transmission of Disease in School

The effects of the COVID-19 pandemic triggered an ample amount of lost time, with context to education and development worldwide. Furthermore, it emphasises the significant need for safeguarding health and well-being to protect the learning outcomes (Kvalsvig et al., 2023). Substantial research now documents both immediate and enduring health consequences of COVID-19 infection, suggesting significant public health ramifications when infection spreads widely among children, primarily on paediatric health outcomes such as multisystem inflammatory syndrome, long COVID symptoms in children, or developmental impacts (Toraih et al., 2021). It bears noting that educators face elevated occupational exposure risks and, according to a United Kingdom research, demonstrate increased vulnerability to post-COVID conditions (Rhodes et al., 2022). The broader familiar consequences of school-based transmission remain inadequately captured in New Zealand's epidemiological surveillance. However, community organisations report considerable disruptions, including reduced parental workforce participation due to childcare responsibilities. The epidemiological pattern resembles other infectious agents, such as respiratory syncytial virus (RSV), which typically enters household environments via school-aged children and poses particular threats to the youngest and eldest family members. Data from the United States indicate that COVID-19 has emerged as the foremost infectious and respiratory cause of mortality among school-aged children (Flaxman et al., 2023).

An estimated 65 million individuals globally experienced post-COVID conditions, including children populations (Davis et al., 2023). While New Zealand research is currently investigating long-term effects following the 2022 Omicron waves, some of the health conditions prevailing after the infection in children include tiredness, cognitive dysfunction, psychiatric disorders, and hypometabolism in critical brain areas (Taquet et al., 2022). Other respiratory system-related issues include shortening of breath to major cardiac illness (Campos et al., 2022), lung-related abnormalities, often blood clotting, and recurring viral infections. Post-infection immunological dysregulation is well established as a post-COVID condition, potentially increasing susceptibility to reinfection and additional infectious diseases, such as immune disorders, issues with the gut microbiome, and hay fever (Kvalsvig et al., 2023). This is of particular relevance for New Zealand, where Group A Streptococcus (GAS) contaminations and higher rheumatic temperature suggest GAS coinfection may exacerbate COVID-19 severity (Sarfraz et al., 2022).

The "dark" 2020-22 history of the pandemic demonstrated that educational facilities in New Zealand remain significant nodes for pathogen transmission. In a post-COVID environment, New Zealand must establish explicit objectives and implement corresponding interventions to safeguard public health and educational integrity amid the unpredictable infectious disease ecosystem (Kvalsvig et al., 2023). Various pathogens, like Group A Streptococcus, exhibit irregular dissemination patterns among children, while concurrent risks of measles resurgence and other outbreak scenarios remain elevated (Baker et al., 2012). This situation presents both a critical necessity and a strategic opportunity for New Zealand to develop and deploy an integrated framework of protective measures against SARS-CoV-2 and additional pathogens, capitalising on the numerous synergistic benefits available in this domain of school spaces. Enhanced indoor air quality and thermal comfort facilitate cognitive function and learning productivity while protecting against COVID-19 and numerous other respiratory pathogens. This exemplifies the potential for interventions offering multiple beneficial outcomes across health promotion and educational effectiveness dimensions (Kvalsvig et al., 2023).

1.5.2 Importance of Designing Buildings for a Post-COVID-19 Era

All four parameters of IEQ (IAQ, TC, Daylighting and Acoustics) have historically constituted a fundamental consideration in public health frameworks and architectural design paradigms, given their profound influence on occupant health and well-being (Kim & De Dear, 2012). Research suggests that environmental characteristics within enclosed spaces substantially affect occupant well-being, satisfaction levels, operational efficiency and, most critically, health outcomes (Afful et al., 2022; de Dear et al., 2016). COVID-19-induced confinement has led occupants to spend more time indoors, posing IEQ as a crucial element in pandemic mitigation strategies (Megahed & Ghoneim, 2021). The emergency to combat the contagion virus has initiated the imperative to prioritise design methodologies that enhance recovery, impede viral transmission, and facilitate improvement.

This global health challenge offers novel perspectives for critical examination within the built environment sector. The post-pandemic architectural response encompassing adaptation, reconfiguration, and reconstruction toward transformed normality addresses the fundamental challenges of inhabiting a post-COVID era (Maturana et al., 2021). Future research investigating beyond the immediate pandemic context is expedient as it offers critical insight into architectural design principles prioritising occupant health. The possibility of future pandemics necessitates a deeper understanding of the interaction between built environments and human well-being (Heymann & Shindo, 2020). Post-pandemic studies with context to built environment have gained significant attention with IEQ studies, specifically addressing indoor air quality, ventilation and thermal comfort (Afful et al., 2022). The majority of the research predominantly investigated airborne viral dispersion and transmission rates in indoor environments (Virbulis et al., 2021). Findings from Dziedzinska et al. (2021) highlight elevated transmission risk within densely occupied, inadequately ventilated environments and areas documenting inferior Air Quality Indices (AQI). A corresponding report evidenced heightened SARS-CoV-2 infection rates (Coker et al., 2020) in such environments. Indoor temperatures, relative humidity, and HVAC systems are significant factors that affect both viral contraction probability and pathogen viability within interior environments. For numerous viral pathogens, including SARS-CoV-2, ambient temperature significantly influences environmental pathogen persistence (Afful et al., 2022). The predecessor of COVID-19, SARS-COV, demonstrated that elevated humidity combined with higher temperatures produced synergistic effects, deactivating coronaviruses and Vice-versa (Chan et al., 2011).

Daylighting considerations and visual comfort parameters intersect with occupant thermal comfort, primarily addressing natural illumination within interior spaces and its impact on viral dynamics (Agarwal et al., 2021). Key considerations include fenestration strategies facilitating natural light penetration through daylighting and appropriate interior luminance levels supporting occupant activities. Findings from De Toro et al., (2021) emphasised that COVID-19 patients had speedy recovery with greater exposure to daylight connections. Another study by Kesik et al., (2019), stated that improvement in sleep cycles due to enough exposure to sunlight helped improve circadian rhythm regulation. Hence, the built environment plays a vital role in mitigation strategies for viral transmission and offering support for recovery (Leng et al., 2020). Interior spaces designed to accommodate physical distancing enable safer social interactions, both passive and active, while reducing pathogen transmission (Chen et al., 2021). Furthermore, improving overall IAQ and TC in indoor spaces not only improves health and well-being but also enhances productivity in every individual (Li et al., 2021). The pandemic presented a transformative opportunity for built environment professionals, policy architects, and building occupants to implement critical improvements to residential and commercial environments, enabling interior spaces to appropriately support occupant comfort, satisfaction, health, and well-being while establishing preparedness for future pandemic scenarios.

1.6 Importance of IAQ and TC in school classrooms

Indoor air quality, thermal comfort, and ventilation rates are fundamental factors in the school's indoor environment. Research conducted in the current area of expertise has been for decades. Optimal IAQ conditions in indoor environments create conducive learning spaces for knowledge acquisition. Findings have also shown that substandard IAQ can adversely impact children's concentrations, learning abilities, cognitive functioning and academic achievement (Sadrizadeh et al., 2022). The prime motive behind school spaces is to offer children an indoor environment where the conditions are optimal for their personal growth. These facilities function as secondary domiciles for students, who allocate substantial portions of their daily activities to these enclosed spaces. Schools represent crucial nodes for children's social engagement within the built environment. Notably, classroom environments exhibit population densities approximately quadruple those observed in conventional office settings (Katafygiotou & Serghides, 2014). The significance of indoor classroom environments is derived from investigated studies and correlations between suboptimal indoor conditions and adverse effects on students' physiological well-being, comfort perception, and educational attainment (Mendell & Heath, 2005). During critical developmental periods, children exhibit heightened susceptibility to environmental exposures, potentially resulting in long-term negative health sequelae, including respiratory pathologies and cognitive impairment (Zhang et al., 2006). Moreover, classroom, in general, represents a higher risk of cross-contamination of aerial illness due to high occupancy and poor maintenance.

The constellation of factors affecting indoor conditions in school classrooms collectively influences children's learning progression, cognitive development, and behavioural and physiological development (Fransson et al., 2007). Among multiple factors and dependents, IAQ, TC, RH and Ventilation are considered the most promising factors that impact students' health, well-being and development significantly (Jia et al., 2021). Additionally, classroom ventilation systems and airflow modalities significantly affect the IAQ and TC (Canha et al., 2016). Numerous studies have demonstrated the impact of poor IAQ, TC and ventilation on health, well-being, academic performance, and physiological and psychological issues associated with short-term and long-term exposure in children. Hence, the next section delves into the importance of thermal comfort and relative humidity on children's overall well-being, academic results, and developmental journey.

1.6.1 Thermal Comfort and Relative Humidity Importance

Indoor thermal conditions in school spaces require additional consideration because children are more vulnerable to environmental stimuli than adults (Mendell & Heath, 2005). Scientific studies on human thermal comfort have stated multiple differences (physiological-anatomical) between children and adults, including different body mass index, respiration rate, metabolic activity, temperature sensitivity, and cardiac functioning outputs (Inbar et al., 2004). Indoor temperature in the occupied built environment is from the equilibrium between thermal gains and losses. The magnitude of heat transfer correlates directly with the temperature differential between interior and exterior environments while being inversely proportional to the thermal resistance properties of construction materials (Wang, 2020). The WHO recommends a temperature range for indoor settings between (18℃- 24℃) (WHO, 2010). However, the WHO temperature range is also supported by CIBSE (2015), which states that temperature setting between 19℃-21℃ and BB 99 &101 with a temperature range of 20℃-25℃ (DfES, 2018). Research by Pierse et al. (2011) shows significant associations between indoor temperature parameters and pulmonary function among asthmatic children's populations, with particularly pronounced effects observed when ambient temperatures declined below 11°C. In this study, 10-year-old children were placed in different temperature settings for part of the day between 20 -30℃. Findings of the performance assessment reveal that children close to a temperature setting of 20℃ showed significant improvement with tasks. In contrast, children near the temperature setting of 30℃ within the same day could not achieve tasks as efficiently as those in the 20℃ temperature setting (Wargocki & Wyon, 2007). Further investigation from the same study showed that for every 1℃ drop (25℃-20℃) in temperature setting augmentation, children could perform mathematical computation and reading comprehension tasks, approximately by 2% improvement to previous findings. In another study conducted in a cohort of elementary schools by Haverinene-Shaughnessy & Shaughnessy (2015), for a temperature range between (25℃-20℃), findings revealed that for every 1℃ drop, children improved their mathematical grade by approximately 10 %. Correspondingly, a study from an American high school revealed a significant decline in academic performance during the hottest time of the year (32℃); close to 12% showed a high failure rate in examinations (Park, 2016). Research by Dorizas et al. (2015) demonstrated a marked thermal satisfaction gradient among students, with complete contentment observed at the lower threshold of 22.5°C, contrasting with comprehensive dissatisfaction at the upper boundary of

25°C. Another investigation by de Dear et al. (2016) established that students tolerate summer thermal conditions within the 19°C-26°C range, with optimal thermal comfort centred at an operative temperature of 22.5°C. Cognitive performance dimensions were examined by Hygge & Knez (2001), who documented superior memory recall performance at the moderate temperature condition of 21°C compared to the elevated thermal environment of 27°C.

Relative humidity (RH), known as moisture, is derived from multiple building materials sources, including internal and external sources. The moisture derived from building materials differs between internal and external sources. Materials release moisture in the indoor environment as they get old (dry out). While hygroscopic building supplies continue to interact with ambient humidity, absorbing and releasing moisture, they cease to function as a primary source of indoor moisture after the initial drying phase (Wang, 2020). Research identifies significant physiological effects associated with RH extremes. Insufficient humidity (lower than 30%) produces itchy eyes and skin allergies (Mendell & Heath, 2005). Excessive humidity (higher than 70%) facilitates the proliferation of allergens, including dust mites, moulds, and bacterial agents (Munir et al., 1995). In addition, to maintain the balance between Rh and Temp. Sterling & Arundel (1985) recommends maintaining classroom RH between 40-60% at (18-24°C) temperatures to optimise comfort while minimising allergen propagation. Analysis by McIntyre (1978) demonstrated enhanced occupant comfort received at 40-50% RH ranges at a constant temperature of 23°C. According to Gilbert Gedeon (2008), the occupant's maximum comfort, approximately 80%, was attained at an RH level of 50% within the temperature setting of 20°C-25°C. Regulatory bodies have established specific parameters for indoor RH to ensure occupant health and comfort. ASHRAE 62.1 initially recommended an RH range of 30-60% (ASHRAE, 1989), subsequently raising the upper threshold to 65% in 2004 and maintaining this recommendation in later standards (ASHRAE, 2004, ASHRAE, 2016). Numerous scholarly researchers have indicated that moisture content variations in the air may have negligible influence on occupant thermal satisfaction when other environmental parameters, ambient temperature, air movement, and radiant temperature, remain within comfort thresholds (Ackley, 2021; Bauman et al., 1996; Djamila et al., 2014). Nevertheless, elevated atmospheric moisture becomes increasingly consequential for thermal perception under conditions of heightened ambient temperature and accelerated metabolic activity (Jin et al., 2017).

Multiple investigations have documented RH conditions in school spaces. A study from New Zealand found that approximately 31% of surveyed classrooms in Wellington out of 35 experienced RH levels exceeding 65% for most of the school hours (McIntosh, 2011). Another study from Germany documented mean RH levels of 38% (range: 22-60%) in approximately 100 predominantly naturally ventilated classrooms (Fromme et al., 2007). Mechanical ventilation systems in American schools demonstrated mean RH values of 38.1% and 39.9%, with 68% and 30% of measurements falling outside the recommended 30-60% range, primarily at the lower extreme (Ramachandran et al., 2005).

The comprehensive SINPHONIE project revealed significant geographic variations in mean classroom RH: Northern Europe (33.4%, range: 6.0-56.1%), Southern Europe (51.4%, range: 25.5-80.4%), Central Eastern Europe (38.7%, range: 20.4-64.2%), and Western Europe (42.7%, range: 23.0-67.8%) (Csobod et al., 2014). These findings suggest that educational facilities across all regions experienced periods outside optimal RH parameters, potentially impacting student health and comfort. The (US EPA) advocates maintaining indoor RH under 60%, with an optimal range of 30-50%, noting that approximately 80% of averagely attired occupants experience comfort at 50% RH (Indoor Environment Divison, 2008).

School spaces experience a high percentage of RH due to multiple endogenous and exogenous sources. Some of it accounts for the respiration process, damp clothing and shoes, and dampness in the surrounding environment and subfloor due to rainwater, temperature differences and precipitation. Effective humidity management requires restricting environmental moisture ingress and facilitating appropriate moisture extraction from interior environments. This dual approach represents a critical consideration for New Zealand school spaces, where ambient relative humidity typically fluctuates between (70-90%) annually (NIWA, 2018). Under these climatic conditions, controlling exterior moisture infiltration becomes essential for maintaining appropriate interior hygrometric parameters. Subsequently, improving the ventilation rates can be directly associated with comfortable indoor temperature and relative humidity can be minimised. The next section explores the importance of improving the ventilation rate. Also, it explains the means of assessing CO_2 levels to justify healthy indoor air quality and its associated impact on children in school spaces.

1.6.2 Importance of Ventilation & Carbon Dioxide

Properly maintaining appropriate indoor environmental conditions in educational facilities depends on effective ventilation systems. Research indicates that ventilation rates up to 20 L/s per occupant correlate with reduced sick building syndrome manifestations and enhanced indoor air quality (Seppänen et al., 1999). Suboptimal air exchange in school spaces affects student comfort, health parameters, and educational performance metrics. Shaughnessy et al. (2006) showed mathematics-standardised assessment outcomes and classroom ventilation insufficiency. Minimum ventilation rates differ among different regions worldwide. Regulatory frameworks for school space ventilation exhibit international and regional variations, typically specifying minimum airflow requirements per occupant or floor area. CO_2 concentration is frequently employed to indicate sufficient air exchange in occupied spaces due to its direct correlation to individual ventilation rates. Studies have documented that insufficient ventilation can result in significant elevations of CO_2 within classroom environments (Fisk, 2017). School spaces employ various ventilation methodologies: natural systems utilising environmental forces, mechanical systems, and hybrid approaches combining multiple technological solutions. Historically, school structures typically lack mechanical ventilation infrastructure, relying instead on managed natural ventilation through strategic window operation (Stabile et al., 2017). The COVID-19 pandemic catalysed heightened awareness regarding ventilation adequacy, prompting the development of comprehensive natural ventilation protocols (WHO, 2020). Natural ventilation predominates in educational facilities across diverse geographic regions, including the United States, Southern and South-Eastern Europe, China, India, Australia, the United Kingdom, Canada (Wargocki et al., 2019) and New Zealand (Ackley, 2021; Boulic et al., 2022; McIntosh, 2011; Ministry of Education, 2022; Wang, 2020). Interventional research demonstrated significant cognitive performance enhancements associated with improved ventilation and reduction in CO_2 concentration from 5000 ppm to 1000 ppm: Word Recognition improvised (+15%), Colourful Word identification (+3%), Choice Reaction (+2%), and Picture Recognition (+8%) all showed measurable improvement under enhanced ventilation conditions compared to low-ventilation scenarios (Bakó-Biró et al., 2012). Another study by Sundell et al. (2011) established correlations between inadequate ventilation rates and elevated prevalence of respiratory symptomatology in educational environments, including respiratory infections, inflammatory responses, short-term absenteeism, and asthmatic manifestations. In the same study, children's absence was found to be decreased by 10-20% when CO_2 levels were recorded below 1000 ppm. A comprehensive California-based investigation by Mendell et al. (2013) examining 162 school classrooms across 28 elementary schools documented a ~1.5% decline in illness-related absenteeism per (l/s/p) of additional ventilation provided. Their findings suggested the potential for further reductions in illness-related absence when ventilation rates exceed 10 l/s/p, with continued benefits potentially extending to 15 l/s/p or beyond. Other significant findings from Finnish research by Turunen et al., (2014) examining 56 schools identified tiredness (~8%), nasal congestion (~7%), and sore head (~5%) as predominant weekly occurring issues, while noise disturbance (~11%), perceived inadequate air quality (~7%), thermal discomfort, and particulate matter represented the most frequently reported environmental factors causing daily classroom discomfort, potentially indicating insufficient ventilation or suboptimal thermal conditions. Another research by Wargocki et al. (2017) found that children improved performance with academic assessment when CO_2 was dropped to 1000 ppm from ~2000 ppm. Similarly, Petersen et al. (2016), exhibited improved accuracy in mathematics puzzles and reduced error evaluation by declining CO_2 ~900 ppm. A relative study of absenteeism by Coley et al. (2007) showed a 5 % decline in attention capacity with a CO2 level of ~ 2000 ppm. In an attendance-focused research, Gaihre et al. (2014) established that within environments averaging 1086 ppm, each 100 ppm CO_2 increment corresponded with a 0.2% elevation in student absenteeism.

Research by McIntosh, (2011) exhibited an average CO_2 level exceeding ~1000 ppm in 37 per cent of NZ classrooms for most of the day during class. Similarly, another NZ study (Cutler-Welsh, 2006), identified CO_2 levels exceeding ~1000 ppm for approximately 80 % of the day in 3 school classrooms in Christchurch. The collective research evidence demonstrates that naturally ventilated school spaces consistently exceed recommended carbon dioxide thresholds (typically ~1000 ppm). The mandatory and recommended guidelines for New Zealand with context to indoor air quality, thermal comfort, ventilation rate, carbon dioxide, window-to-wall ratio, occupancy and all other requirements related to thermal resistance for wall, floor, ceiling, and windows are exhibited in the document called Designing Quality Learning Spaces (DQLS), which is discussed in the next section with its origin, purpose and scope along with its journey of iteration to the current state of time.

1.7 Designing Quality Learning Spaces (DQLS) Transition: COVID-19

The Designing Quality Learning Spaces (DQLS) documentation, initially published in (2007) as separate guides addressing Heating and Insulation alongside Ventilation and Indoor Air Quality, underwent consolidation in 2017 (Version 1.0) and subsequent comprehensive revision in 2022 (Version 2.0). These technical specifications, developed collaboratively between the Ministry of Education and expert advisors, establish parameters for environmental quality in educational facilities throughout New Zealand's extensive portfolio encompassing over 15,000 buildings and 35,000 teaching spaces across approximately 2,100 schools. The New Zealand Ministry of Education develops the document versions 1.0 (2017) and 2.0 (2022).

DQLS Version 1.0 (2017) Purpose: The iteration primarily outlined technical specifications for designers developing appropriate educational spaces fit to purpose, including provisions for flexible learning spaces (FLS) that facilitate innovative learning environments (ILE) aligned with national curriculum standards. The initial 2017 framework (Version 1.0) represented a foundational consolidation of previously disparate guidance materials concerning thermal regulation and ventilation in educational settings. This inaugural unified document integrated 2007 guidelines on Heating and Insulation with Ventilation and Indoor Air Quality provisions, tailoring them to accommodate contemporary pedagogical approaches and adaptive learning environments. The document employed a straightforward classification of guidelines as either obligatory or advisory, establishing fundamental parameters for implementation by design professionals without explicitly connecting these standards to broader educational infrastructure objectives (Ministry of Education, 2017a).

DQLS Version 2.0 (2022) Purpose: The subsequent version contextualises this document within a broader regulatory framework. This document is one component of the Ministry of Education’s DQLS collection, which holistically addresses all four parameters of IEQ: indoor air quality, thermal comfort, illuminance and acoustics requirements. This version establishes clear relationships with the companion document, Designing Schools in New Zealand (DSNZ) guidelines, which incorporates additional specifications regarding the Acoustics metric and building envelope. The DQLS V2.0 targets architects and building engineers to maintain the fundamental purpose of providing technical guidance while more explicitly acknowledging the document's role in supporting property managers overseeing educational facility projects and emphasising creating environments that are functionally appropriate for their educational purpose. Version 2.0 represents a significant strategic alignment with Te Rautaki Rawa Kura - School Property Strategy 2030, particularly emphasising the Ministry's commitment to delivering quality learning environments that support teaching, learning, and occupant wellbeing. This comprehensive revision introduced the differentiation between non-negotiable standards and flexible design recommendations while significantly elevating performance requirements across air quality indicators, thermal regulation metrics, temperature (overheat) limitations, and ventilation delivery specifications. Notable enhancements included climate-responsive conditioning considerations, economic evaluation tools for system longevity assessment such as the Life Cycle Assessment (LCA) tool, enhanced building envelope thermal resistance specifications, updated regional climate classifications, and rigorous verification protocols spanning conceptual development through operational implementation. These refinements collectively represent a more sophisticated, performance-oriented approach to environmental quality management in educational facilities (Ministry of Education, 2022). The fundamental distinction between Version (1.0) and Version (2.0) is explained in chapters 3 and 4 of this research study.

1.8 Research Aim, Questions and Objectives of the Study

Anecdotal evidence shows that most NZ primary school classrooms do not provide the appropriate IAQ and TC environment for learning; rather, they present a favourable environment for viral transmission. This was evident in the recent COVID-19 pandemic. To prepare for future pandemics, this study is tasked with optimising the IAQ and TC design guidelines for post-COVID-19 classrooms that are fortified to mitigate the spread of various diseases. Hence, the following research aim, questions and objectives are set to be achieved:

Aim:

This study aims to develop an Indoor Air Quality (IAQ) and Thermal Comfort (TC) best practice for post–COVID–19 in New Zealand primary school classrooms.

The study was categorised into three core research questions to achieve the above aim, which were further divided into the research objectives. Each objective is categorised into an individual chapter, which comprises the overall completion of the study.

Research Questions:

RQ1. *How do the current DQLS V (2.0) IAQ and TC design guidelines for New Zealand primary school classrooms compare with international standards from OECD countries, and what adaptations are necessary for the post-COVID-19 environment across the six climate zones?*

RQ2. *What are the key limitations of existing IAQ and TC design guidelines when applied to post-COVID-19 classroom environments in New Zealand's six climate zones, and how do these limitations impact classroom health and safety?*

RQ3. *What specific modifications to the DQLS version (2.0) would create optimal IAQ and TC design guidelines for New Zealand primary school classrooms that are both practicable and effective across the six climate zones?*

Research Objectives:

To answer these questions, the following objectives guided the research activities:

1. *To critically evaluate the DQLS V (2.0) IAQ and TC design guidelines with international guidelines (OECD Countries) for the post-COVID-19 environment for six climate zones in New Zealand.*

2. *To ascertain the suitability of current IAQ and Thermal Comfort design guidelines for six climate zones in New Zealand.*
3. *To design a post-COVID-19 optimal IAQ and TC standard for six climate zones in New Zealand primary school classrooms.*
4. *To validate the developed optimal post-COVID-19 IAQ and TC design guidelines for six climate zones in New Zealand primary school classrooms.*
5. *To recommend improvement opportunities for DQLS version (2.0) to achieve healthy primary school classrooms in New Zealand.*

1.9 Scope of the Study

The study focuses on developing the enhanced best practices for IAQ and TC in New Zealand primary school classrooms in six climatic zones. The six climatic zones selected for this study represent New Zealand's climatic conditions. One city from each climate zone was selected to cover the geographical context of New Zealand, namely Auckland, Hamilton, Wellington, Rotorua, Christchurch and Queenstown. These cities strategically represent the diverse geographical and climatic conditions across New Zealand, ensuring the research findings would be applicable nationwide. Each city represents distinct weather patterns that affect building performance differently. Because this research is centred on the DQLS document, the study chose two reference design models of primary school classrooms. The selected two primary school classroom typologies are recommended and provided by the Ministry of Education New Zealand as they align with the DQLS document. Using these Ministry of Education-endorsed typologies ensures the research directly applies to current and future primary school-building projects in New Zealand. The study entailed conducting a systematic document analysis and comparative analysis of existing DQLS V 1.0 to DQLS V (2.0) IAQ and TC design guidelines against international standards from OECD countries, evaluating their suitability and efficacy across New Zealand's six distinct climate zones. This comparative identifies critical guideline elements requiring adaptation to address viral transmission concerns while maintaining optimal classroom learning environments. The study generated evidence-based recommendations for specific modifications to the current building design model and guidelines through multi-criteria optimisation models applied to both New Zealand classroom typologies. The changes and recommendations consider both overall health and academic performance. The study developed parametric models to visualise optimal classroom operations incorporating the proposed design modifications. These were used to develop enhanced guidelines and strategies for post-COVID classrooms, which school design experts validated. Later, to validate the findings for optimal post-COVID-19 primary school classrooms, industrial validation with experts in school designing, architects, building scientists, and facility managers was conducted through qualitative and quantitative analyses.

The study specifically targets primary school classroom environments, acknowledging their unique occupancy patterns, spatial configurations, and ventilation requirements. By focusing on the DQLS V (2.0) framework, this study intends to deliver actionable improvements for key stakeholders, including architects, building practitioners, facility managers, designers, and engineers. The scope encompasses immediate interventions for existing facilities and design principles for future educational buildings, with particular attention to the intersection of indoor air quality, thermal comfort parameters and ventilation requirements that support occupant well-being and window enhancement with transmission mitigation objectives.

1.10 Limitations of the Study

Despite its comprehensive approach, this research operated within several important constraints that warrant acknowledgement. The study focuses exclusively on primary school classrooms in New Zealand, limiting direct transferability to other educational environments such as secondary schools, tertiary institutions, or specialised learning spaces. While this focused scope of the study enhances precision for the primary school environment, it necessitates limitations when generalising findings. The study primarily addresses IAQ and TC parameters, with limited exploration of other Indoor Environmental Quality factors such as lighting, acoustics, and human interactions. These components may interact with the studied variables in complex ways. The analysis relied predominantly on parametric modelling rather than extensive field testing across all climate zones, presenting an inherent limitation in real-world application verification. The acoustics research, weather tightness, bridging, and moisture control have not been further studied. Also, the research emphasises physical and operational modifications rather than behavioural investigations or educational approaches that might complement environmental strategies. Economic feasibility analysis remains limited to general implementation considerations rather than detailed cost-benefit analyses that would better inform resource allocation decisions. Additionally, while the study addresses the post-COVID-19 context specifically, rapid evolution in understanding of respiratory disease transmission may affect the longevity of certain recommendations. Climate change impacts on future thermal conditions are acknowledged but not extensively modelled within the study parameters, potentially affecting the long-term applicability of thermal comfort guidelines. These limitations establish important boundaries while maintaining the study's focused contribution to improving New Zealand's primary school classroom environments. More limitations are discussed in Chapter 7, section 7.4.

1.11 Significance of the study

This study addresses a critical public health concern by developing evidence-based IAQ and TC best practices for New Zealand primary school classrooms in the post-COVID-19 context. The research establishes the fundamental significance of indoor air quality and thermal comfort, demonstrating their profound impacts on student cognitive performance, health outcomes, and overall educational efficacy. Through rigorous analysis of contemporary scholarly literature, the investigation elucidates the mechanisms of viral transmission within indoor environments and identifies specific parameters that contribute to contamination pathways.

The research systematically identifies critical gaps in New Zealand's current classroom environmental design standards, contextualising these weaknesses against international benchmarks and scientific consensus. The study synthesises emerging scientific findings regarding transmission mitigation strategies and environmental optimisation techniques by comprehensively examining global norms and guidelines. The investigation's methodological innovation lies in its application of multi-criteria optimisation through parametric modelling of Indoor Environmental Quality (IEQ) parameters. It enables the visualisation of classroom typology operations with optimal design modifications for enhanced IAQ and TC.

The distinctive comparative findings from this research directly contribute to improving children's learning environments in educational settings. The study deliberately aligns with the Designing Quality Learning Spaces Version (DQLS V2.0) framework, providing actionable recommendations for stakeholders, including architects, building practitioners, facility managers, designers, and engineers. Furthermore, it equips school property management teams with crucial insights regarding indoor environmental health maintenance, emphasising the importance of operational factors such as manual window operation for optimal airflow management, contaminant mitigation, and carbon dioxide concentration control—factors directly linked to student well-being and academic performance.

1.12 Structural Outline of the Thesis with Publications List

This doctoral dissertation holds a total of 7 chapters. Each chapter plays a significant role from initiation to the completion of this study. This doctoral dissertation adheres to the Massey University directions for the presentation of this dissertation by several publications. This dissertation comprises five publications, including three journal articles (one published and two under-review) and two conference publications (published). Each publication with context to this study adds significant importance to formalising this thesis chapter. A brief structural outline of all the chapters (one to eight), including introduction, methodology, discussion, validation, conclusion and recommendation, is provided below:

Chapter 1 introduces this study and the area of research chosen. Later, it gives an overview of IEQ and COVID-19, with which this study shaped a robust form and identified the problem statement. Further, it delves into the nature of the study with school classrooms and children, its impacts and influence on health and well-being, and why it is necessary to maintain a healthy indoor environment in compounded built structures. Further, it exhibits the aim, research questions, and objectives, as well as its scope, limitations, and significance.

Chapter 2 outlines the detailed methodology adopted for this study from beginning to completion. The beginning of this chapter explains in detail the necessary unpinning of research methodology in terms of research philosophies, epistemological perspective, qualitative perspective, quantitative perspective and pragmatic perspective (mix-methods). In the middle of this chapter, the complete thesis flow chart with the research objectives and methodology is applied individually and is explained in the phases from commencement to finalisation. Later, the same chapter discusses the data collection, tools, analysis techniques applied, and reliability of validation, followed by a detailed explanation of the ethical code and conduct.

Chapter 3 outlines the comprehensive rationale for the Designing Quality Learning Spaces (DQLS) document, published by the Ministry of Education New Zealand. This chapter comprehensively compares the DQLS V1.0 (2017) vs DQLS V2.0 (2022) to identify the potential changes, strengths and weaknesses along with similarities and differences within both documents. Also, the significant changes adopted in the new version and its alignment with the strategic enhancement of Te Rautaki Rawa Kura - School Property Strategy 2030 is highlighted, emphasising the Ministry's commitment to delivering quality learning environments that support teaching, learning, and occupant wellbeing. This chapter is published by Arya, V., Rasheed, E. O., Samarasinghe, D., & Wilkinson, S. (2023, November). A Review of Indoor Air Quality and Thermal Comfort Guidelines for New Zealand Primary School Classrooms: A Comparison of DQLS Document (Old Versus New). In *International Conference on Engineering, Project, and Production Management* (pp. 791-804). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-56544-1_50

Chapter 4 outlines the comparative analysis of DQLS V2.0 with international standards from OECD countries. This chapter, DQLS V2.0, is compared with ASHRAE 62.1, CIBSE TM 57, EN-15251 and BB 99&101 with context to IAQ, TC, Ventilation rate, CO2, Occupancy, and Occupant's density/ classroom size. The rationale of this chapter is to ascertain the IAQ, TC, ventilation rate and CO_2 guidelines for DQLS V2.0 against international guidelines to identify new opportunities for New Zealand primary school classrooms. This chapter is published by Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S., & Wilkinson, S. (2024). "Comparative Analysis of Indoor Air Quality and Thermal Comfort Standards in School Buildings across New Zealand with Other OECD Countries". *Buildings*, *14*(6), 1556. https://doi.org/10.3390/buildings14061556.

Chapter 5 outlines the parametric modelling findings across local and international comparative standards used in this study. This chapter explains the simulation methodology conducted in this research. The two school classrooms' design references of New Zealand, Avalon and Canterbury block, are simulated simultaneously with DQLS V2.0 and international standards from OECD countries. This chapter exhibits the significance of adopting Rhino 7 software, with Ladybug and Honeybee tools in Grasshopper's plugin to conduct parametric modelling. The multi-criteria optimisation (MCO) technique was employed to evaluate the metrics of IAQ, ventilation, thermal comfort and building envelope. The variables used in the study involved temp, rh, ventilation rate, CO_2, classroom dimensions, WWR%, occupancy, occupants' density, thermal insulation (roof, wall, ceiling, floor, windows), dew point and dry bulb temp and generic classroom-built structure details (number of classrooms and year of construction, toilets, cloakroom, occupancy schedule, and EPW weather data). The multi-criteria optimisation technique was used to synthesise the findings of both classroom typologies simulation against DQLS V2.0 and international standards from OECD countries. The multi-criteria optimisation technique helps to develop the optimal IAQ and thermal comfort best practices with the best combination of WWR %, ceiling height adjustment, window vertical placement, improved R-value for climate-specific zones and Clo value. This chapter is submitted in parts 1 and 2 of journal articles. This first journal article is submitted to "*Building Journal*" from "*MDPI*" by *Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S.,(2025). "A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New Zealand's Six Climate Zones (1): The Avalon Typology" (Under- Review – Buildings 3595956).* The second journal article is submitted to "Smart and Sustainable Built Environment" from "Emerald Publishing" by *Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S.,(2025)."A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New*

Zealand's Six Climate Zones (2): The Canterbury Typology" (Under-Review - SASBE-04-2025-0168)

Chapter 6 exhibits the validation phase adopted in this study. This chapter explains the methodology adopted to conduct the semi-structured interviews and Likert scale assessment following the findings of the parametric modelling of both school classroom typologies against all standards. This chapter comprehensively discusses the discussion of the open-ended question with context to (the simulation methodology, software selection applicability, and comparison of international standards with DQLS 2.0, and optimal design changes toward post-covid19). The Likert scale questionnaire ascertains the results and findings regarding adaptive thermal comfort, energy analysis, carbon dioxide, and optimal design changes in the building envelope. This chapter is published by Arya, V., Rasheed, E. O., & Samarasinghe, D. (2025 February). "Validation of Optimal Indoor Air Quality and Thermal Comfort Design Guidelines for Post-COVID-19 New Zealand Primary School Classrooms". Holistic Living: Sustainable, Affordable, and Resilient Built Environment. *In Proceedings of the 8th New Zealand Built Environment Research Symposium.* Cham: Springer Nature Switzerland.

Chapter 7 offers a comprehensive conclusion and recommendation of research outcomes, situating findings within a theoretical framework and building a connection between the literature review and simulation analysis, followed by a validation procedure. Furthermore, it critically evaluates the significance of multiple analyses toward strengths and weaknesses by offering scientific explanatory mechanisms. It synthesises and integrates all the key findings from all the above chapters. Also, it evaluates the achievement of the established research aim of this study. This chapter articulates the contribution of the study's scholarly articles, recommendations toward school management, and practical implications for industry and academic professionals who belong to the built environment. Additionally, it acknowledges the research area's inherent constraints and proposes the direction for future research endeavours.

2. Research Methodology

2.1 Philosophical Keystones to Methodology

A researcher's philosophical orientation essentially influences the choice of research design. Adopting an appropriate research philosophy facilitates smoother research development and more robust findings. Two primary philosophical viewpoints that structure the research process are ontology and epistemology.

Ontology addresses questions about existence and its nature (Bell et al., 2022). This perspective observes the relationship between human actions and social realism. The ontological viewpoint can be categorised into objectivism and constructionism. The objectivist stance maintains that social realism exists independently of distinct perception, suggesting a single, objective reality. Conversely, constructionism proposes that reality is not singular but varies according to individualistic observers, constructed through personal experiences (Bell et al., 2022). Understanding ontological philosophy is essential when developing new theories or testing existing ones.

Epistemology concerns what constitutes acceptable information within an area of research. This viewpoint clarifies the relationship between the scholarly researcher and their area of research. The epistemological spectrum ranges primarily between positivism and interpretivism.

Positivism approaches the area of research with the belief that reality is present, independent of the scholar, and can be assessed objectively through systematic methods. This approach strongly favours deductive theory. Positivists follow the principles of reasoning in their area of research and rely extensively on observations and experimentation for data collection. Consequently, testing and scrutinising existing models and theories is popular in this approach (Easterby-Smith et al., 2012). Quantitative research methods align well with positivism (Saunders et al., 2009).

Conversely, interpretivism emphasises subjectivity and maintains that the realism of the area of research depends on societal ideas (Bell et al., 2022). Occasionally denoted as 'Phenomenology', this viewpoint suggests mutuality between individuals and the world. Distinct settings and individual experiences yield varying findings. Contrary to positivism, interpretivism strongly depends on inductive theory and typically employs qualitative research methods. A comparative analysis of both viewpoints exhibited by renowned scholars is stated in Table 2.1.

In this research, the workflow aligns with epistemological viewpoints, i.e., positivist and interpretivist. Objective 1 typically involves a literature review and critical evaluation of technical reports, Journal and Conference Articles, Government Documents and Standard Guidelines. The approach aligns with interpretivism, though it has some elements of positivism in comparing parameters like temperature, CO_2 levels, ventilation rates, occupancy, and classroom size across different international standards in contrast to DQLS v2.0. Objectives 2 and 3 predominantly align with the positivist approach, as they used descriptive statistics and simulation analysis to measure and evaluate the current suitability of IAQ and TC parameters across all the standards for six climate zones of New Zealand. Then, the simulation tools and algorithms are used to develop an optimal design based on statistical data in conjunction with parametric modelling across six climate zones. Objective 4 aligns with positivism through mean score analysis for the Likert scale questionnaires and interpretivism through thematic analysis of open-ended questions and discussions to gather subjective feedback to validate the optimal IAQ and TC design guidelines for New Zealand primary school classrooms.

Table 2.1: Comparative Framework: Epistemological Approaches

Source: (Bell et al., 2022; Saunders et al., 2009)

Characteristics	Positivist Viewpoint	Interpretivist Viewpoint
Research Focus	Sciences	Individual Interactions
Research Stance	Objective	Subjective
Research Primary Focus	Natural Phenomena	Societal Reality
Core Assumption	External Reality	Constructed Reality
Research Goal	Information Gathering	Interpretation of meaning
Theoretical Approach	Predominantly Deductive	Predominantly Inductive
Sample Characteristics	Extensive	Limited but Comprehensive

2.2 Approach to Area of Research

A well-structured research strategy helps conduct research systematically. The design of the research strategy must build a connection between the objectives of the study, the data set methodology, and its analytical techniques. According to the epistemological method, this area of research aligns with three specific methodologies, namely qualitative methodology, qualitative methodology, and the mix of both, which is called mixed methods. The approach to the area of research comparison is presented in Table 2.2. The researcher adopts a combination of qualitative and quantitative approaches, also termed a mixed method approach. Table 2.3 describes each type of analysis method addressing the objectives of this research.

Table 2.2: Research Approach Comparison

Source: (Bell et al., 2022; Saunders et al., 2009)

Element	Qualitative Approach	Quantitative Approach
Research Process	Inductive	Deductive
Theoretical Relationship	Generating	Testing
Ontological Position	Constructionist	Objectivist
Epistemological Stance	Interpretivist	Positivist
Societal Viewpoint	Dynamic and evolving	External and Objective
Analytical Methods	Descriptive	Statistics
Sample Size Tendency	Limited	Extensive

Qualitative study is applied to the concept of understanding words over mathematical values. It views societal facts as dynamic, changing with time, connected to individual experiences focusing on theoretical concepts. The methodology for such an approach includes open-ended assessments and interviews in a questionnaire discussion format, allowing freedom of speech to every participant. Conversely, Quantitative study is applied to data sets and their analysis, which involves statistical mode. It applies a deductive hypothesis based on scientific evidence to measure the existing models. Findings are validated with numbers and statistical tools used in the analysis; such an approach does not involve individual viewpoint participation (Bell et al., 2022).

Meanwhile, in the mixed-method approach, elements from both approaches are applied based on the requirements of the body of knowledge for research. Hence, some researchers have considered the mixed method approach a robust solution to the limitations of the above two methodologies (Amaratunga et al., 2002). When applied, such methodology enables the researcher to collect necessary data sets from qualitative and quantitative sources simultaneously. Considering the potential of such a methodology, the researcher approached the current study with a mixed methods approach. From a subjective (qualitative) viewpoint, it facilitates the critical comparative evaluation of technical information, government documents, scholarly articles (conference and journal), and international standards and guidelines set by OECD countries presented in Table 2.3 for objective 1. The qualitative analysis also enabled the adoption of the right simulation software selection, which suits this study holistically and meets the performance evaluation of the IAQ and TC parameters that directly influence the indoor environment. Also, the research problem statement is identified from the literature review, document analysis, and content analysis of scholarly articles and international standards from OECD countries. Hence, this enables a deep understanding of current IAQ and TC standards across different geographical regions (national and international).

From an objective (quantitative) viewpoint, it facilitates the synthesis and systematic comparison of IAQ and TC influencing parameters between international and DQLS v2.0 documents. Objectives 2 and 3 rely on quantitative analysis, as stated in Table 2.3. The computational modelling using (Rhino 7) software and descriptive analysis enables identifying the appropriateness and applicability of current IAQ and TC standards with context to six climate zones of New Zealand for primary school classrooms. The comparative computational modelling outcomes identify the adequacy and inadequacy of the indoor environment in New Zealand primary school classrooms. Objective 4's validation approach adopts qualitative and quantitative viewpoints through semi-structured interviews involving academic and industrial experts' perspectives. The quantitative approach is displayed in the mean score analysis for close-ended questions and thematic analysis for open-ended questions on the proposed design guidelines for the COVID-19 scenario. Hence, by integrating such a balancing approach, the research benefits from both the contextual constructs and numerical precision, which is significant for developing the optimal IAQ and TC design guidelines for New Zealand primary school classrooms.

2.3 Research Design

The functional property of a research design acts as a structured blueprint that facilitates the achievement of research objectives by establishing connections within research questions and empirical datasets (Yin, 2021). It serves as a design phase description, creating different phases between the research questions, qualitative data and quantitative data collection and the types of analysis involved. Multiple factors influence the formulation of a research design, with research aims and objectives, philosophical underpinnings, and available chronological and material resources playing central roles in shaping this framework (Saunders et al., 2009). Additionally, scholarly perspectives suggest that the experiential backgrounds of study participants and investigators should be recognised as significant elements when developing a comprehensive research design (Creswell & Clark, 2017).

This research aims at optimal IAQ and TC in New Zealand school classrooms, and it is designed in five phases, each contributing to individual research objectives presented in Figure 2.1.

In phase 1(Objective 1), preliminary studies on IAQ, TC, ventilation and carbon dioxide in school classrooms were reviewed to understand the basic impact of these IEQ factors on health and well-being. Later, as this research was initiated during the pandemic (COVID-19), the literature search was extended to correlate the viral transmission within enclosed spaces. Numerous epidemiological, neuropsychological, mixed-methods, post-occupancy evaluations (POEs), longitudinal cohort studies, building science intervention studies, environmental exposure, and cross-sectional scientific evidence scholarly articles were articulated. The search covered health, well-being, performance, activities, physiological stress, fatigue, allergies, respiratory symptoms, long-term health implications, metabolic deficits, cognitive disorders, and memory-related implications continued to date in the form of a literature review within similar areas of research. They were reviewed to provide a good foundation for this research in relation to the New Zealand context. As discussed in Chapter 1, see sections 1.2 and 1.5.

Furthermore, in the same sections, the findings from the scholarly articles were discussed in reference to their suitability and appropriateness for a post-COVID-19 in-school classroom scenario. Additionally, it discusses the COVID-19 impact on New Zealand school classrooms with context to academic performance, children with multiple issues such as stress management, and behavioural and physiological implications with context to global scholarly research. Hence, looking at the detrimental impact of COVID-19 and its additional association with poor IAQ and TC, it was significant to consider public health frameworks and architectural design paradigms (re-structure, re-assess, re-design), given their profound influence on health and well-being of both children and adult. Furthermore, in the same chapter, section 1.6 discusses the determinants of compromised (IAQ and TC) and explains its negative impact and positive influence, which helps to design the aim, research questions and research objectives.

After identifying the determinants, the standards and guidelines were reviewed to ensure the structuring of the study. First, New Zealand standards and guidelines were assessed from DQLS V1.0 (2017) vs DQLS V2.0 (2022) with context to key differences, strengths and weaknesses alongside scholarly interventions studies on IAQ, TC, ventilation and carbon dioxide from New Zealand in past decades. The analysis involved a content analysis between the two DQLS documents for the above parameters and the significant updates made in building design features and physics (see Chapter 3). After scrutinising the latest DQLS V2.0 with its strengths, changes and differences, the comparative analysis was extended to international standards from OECD countries with similar climatic conditions (ASHRAE 62.1, CIBSE TM 57, EN-15251 and Building Bulletin 99&101). A similar approach was taken for the comparative analysis with these international standards against DQLS V2.0, with a more extensive literature review of IAQ and TC parameters. The findings supported the recommended scientific interventions for optimal IAQ and TC in New Zealand primary school classrooms, with more recent research on COVID-19 (see Chapter 4).

In phase 2 (Objective 2), the simulation assessment was conducted with computational modelling, considering the fundamentals of building physics. Multiple parametric simulation software was researched to select the best fit for the purpose of the study. Two stages were involved in data gathering; firstly, DQLS V2.0 for Avalon and Canterbury blocks were simulated in all six climate zones to identify the limitations and appropriateness of the post-COVID-19 situation. Secondly, international standards were simulated in the same blocks to compare with DQLS V2.0 findings to ascertain the limitations and appropriateness.

A total of five simulation software performing (simulation modelling) were assessed based on open-source, parametric modelling, energy analysis, adaptive thermal comfort/ daylight analysis, ventilation/carbon dioxide graphics and building simulation, namely Climate Studio, Rhino 7, IES-VE, Design Builder and Sefaira. Of all five simulation software, Rhino 7 attained the maximum points to be the best-fit software for this study, followed by numerous other scholarly research interventions (see Chapter 5). For the simulation, two case study school typologies provided by the NZ Ministry of Education (MoE) for designing school buildings between 1950 and 2000, Avalon Block and Canterbury Block, were selected. The Ministry of Education constructed numerous schools during the 1960s, which account for approximately 90% of all primary school classrooms in New Zealand. Many of these structures include various block designs, such as Avalon and Canterbury. (Swarbrick, 2012; Crooks et al., 2023). The design characteristics of these two classroom typologies were used to model the school classroom blocks simulated in this study. Later, the Grasshopper plugin with inbuilt features for ladybug tools (LBT) and honeybee tools (HBT) was used to design the classroom-built features based on occupancy, occupant density, WWR%, construction year, built materials (roof, wall, ceiling, heights, windows and doors with fenestration along to their specific R-value). Once the rhino-modelled classroom blocks were ready, they were imported to the Grasshopper plugin for the built-structure specification.

Many iterations were conducted; the classroom blocks were combined with other geometry design features to simulate various design options. To evaluate the parameters for IAQ, TC, ventilation and CO2, different components of LBT and HBT were considered. For all six climate zones, the weather file (EPW) used was from the climate depository, allowing the actual weather data simulation of selected cities within each climate zone (Auckland, Hamilton, Wellington, Rotorua, Christchurch and Queenstown). After completing all the necessary features, the simulations were conducted with Energy Plus, and input parameters for assessing adaptive thermal comfort, energy analysis, daylight, ventilation, and carbon dioxide based on the OECD country's IAQ and TC standards were used. Then the simulation results were returned to visual formats within Rhino. The components opted for data visualisation for the above parameters: Adaptive thermal Comfort (TCP, HSP and CSP), Daylighting (cDA and UDI), Energy (Cooling, Heating, and Infiltration loads), Ventilation rate effectiveness for CO_2.

In phase 3, similar modelling steps were followed. Robustness analysis was conducted to determine the most influential parameters across all the simulations and incorporate the significant optimal changes to the design features of the Avalon and Canterbury blocks for all six climate zones. The development of optimal design parameters was based on the findings of phase 2. With extensive literature review support, certain changes were adopted to ceiling height for more volume in the classroom for better airflow, alongside window placement to minimise transmission of environmental pollutants, increasing the R-value in two specific climate zones (CHCH and QTN), minimising WWR% and increasing Clo value. After incorporating this design and geometric changes in both Avalon and Canterbury blocks, again parametric simulations were performed using Energy Plus, and comparative analysis and sensitivity analysis were conducted between previous DQLS V2.0 and OECD standards to see the optimal changes findings for a post-covid-19 scenario. The data visualisation of results for adaptive thermal comfort (maps), energy analysis (charts) and carbon dioxide (graphs) are provided in the supplementary file name (simulation outcomes).

In phase 4, a validation of the designed optimal post-COVID classroom was conducted through a survey of industrial and academic experts. The validation process included an open-ended questionnaire designed to evaluate the practicality and appropriateness of the simulation process and the multi-criteria optimisation carried out. The questions covered the experts' opinions and perceptions of the design changes described in phase 3 for optimal IAQ and TC in New Zealand primary school classrooms. Likert scale was designed for 5 points scale (strongly agree to strongly disagree). This was followed by an open-ended section for their comments. Following a systematic ethics procedure, a consent form and participation information sheet (PIS) were provided to the participants. They included all necessary information such as interview procedures, approximate timing, confidentiality, data protection, voluntary participation and ethics code and conduct. The selected participants included architects, building assessors, building data analysts and scientists, directors, environmentalists, BIM modellers and researchers with a minimum of 5 years of experience to 25 years of experience from the New Zealand industrial and academic area who have previously worked with school designing, the external and internal validity of simulation findings (see Chapter 6.) Based on their recommendations, a revision of the simulation process was to be conducted if required.

Phase 5 involved the synthesis and integration of all the above phases, finalising the conclusion in Chapter 7. The conclusion summarised the overall findings of this study and recommendations provided during the validation stage. The additional recommendations were related to the environment of the classroom, where teachers and caretakers play a vital role in experiencing the real issues and what measurable steps (facilities management) can be taken at the individual level by teachers and caretakers to improve the classroom environment along with certain established protocols by international bodies EPA, WHO, Harvard (school for Health), REHVA and CIBSE.

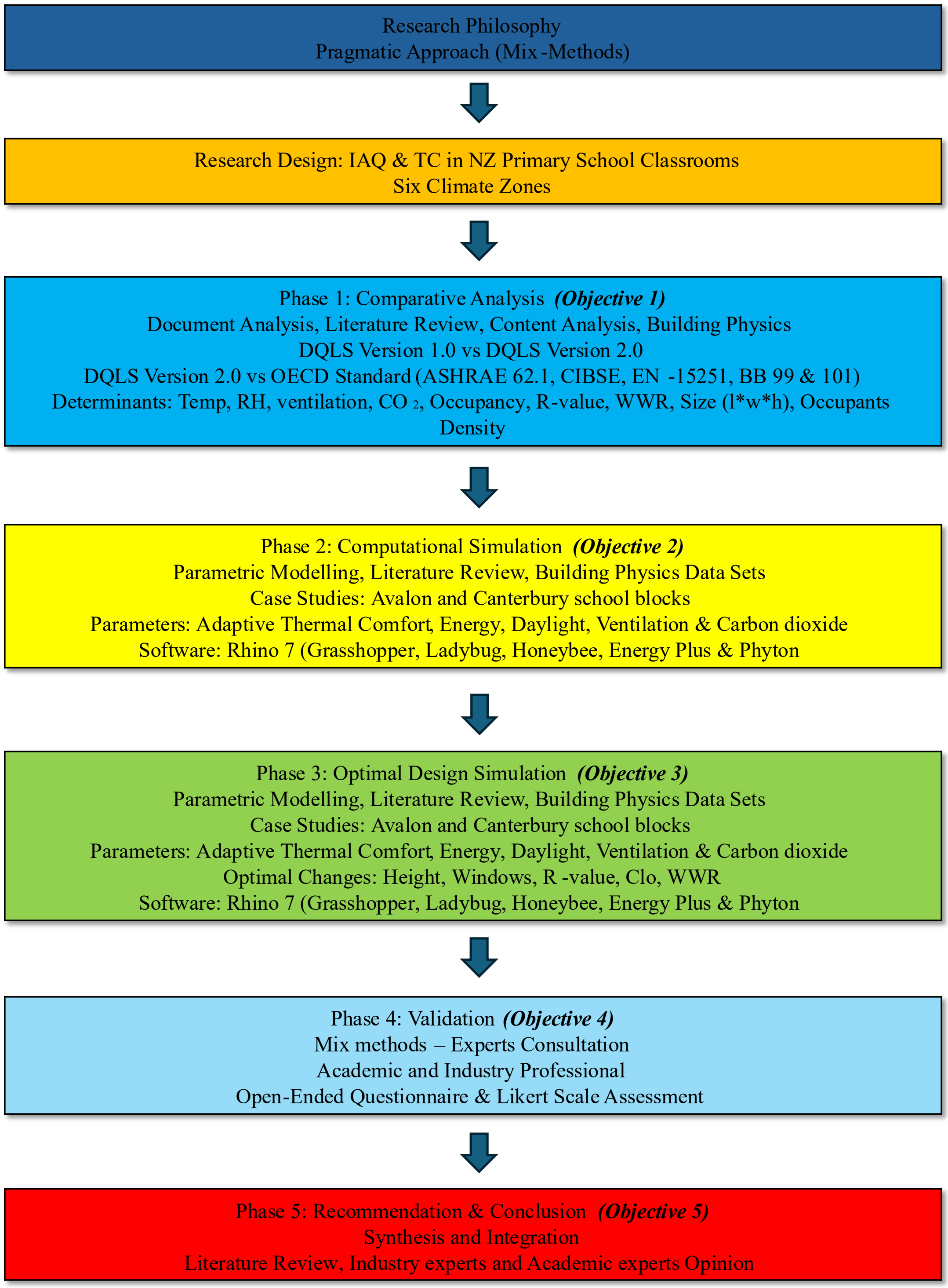

Figure 2.1: Research Design Chart

2.4 Data Collection and Analysis Tools

This research focuses on evaluating, ascertaining, designing, validating and recommending optimal IAQ and TC guidelines for six climate zones in New Zealand school classrooms. Given the comprehensibility of the nature of the research and the adoption of a mixed methods approach, the research is outlined in five phases, explained in Figure 2.1, the research design chart. The methodology applies qualitative and quantitative data collection and analysis techniques across multiple phases (see Section 2.3). These are detailed below.

Table 2.3 Research methods and type of analysis techniques

Objectives	Source of information	Type of Analysis
Objective 1	Literature Review (Technical reports Journal and Conference Articles Government Documents) Standard Guidelines (ASHRAE 62.1, CIBSE, EN-15251, BB99&101 and DQLS v(1.0) & (2.0))	Content Analysis Comparative Analysis Document Analysis
Objective 2	Government Documents and Standard Guidelines (ASHRAE 62.1, CIBSE, EN-15251, BB99&101 and DQLS v(2.0))	Descriptive Statistics Simulation Analysis (Rhino7), Grasshopper, Ladybug, Honeybee
Objective 3	Government Documents and Standard Guidelines (ASHRAE 62.1, CIBSE, EN-15251, BB99&101 and DQLS v(2.0))	Descriptive Statistics Simulation Analysis (Rhino7), Grasshopper, Ladybug, Honeybee
Objective 4	Validation (Semi-Structured Interview) Open-ended and close-ended	Thematic Analysis Mean score Analysis

The following types of analysis are discussed below in section 2.4.1.

2.4.1 Content Analysis

Content Analysis is used in objectives (1, 2, 3 and 4). In this research, content analysis assisted to systematically identify the standards, guidelines, and international documents for school design and technical reports content in analysable elements. This type of analysis allows researchers to use a methodological and impartial approach to examine qualitative information necessary for the area of research. The mode of information collection can be written, graphical or spoken formats (Hashemnezhad, 2015). Researchers employ this analytical strategy when evaluating scholarly publications, investigating case studies, and processing semi-structured interviews. The technique facilitates the identification of key patterns within qualitative data, which allows researchers to gather information into distinct categorisations to enhance the interpretability.

2.4.2 Comparative Analysis

Comparative Analysis is used in objectives (1, 2 and 3). In this research, comparative analysis assisted in identifying and directly comparing IAQ and TC impacting parameters such as temp, RH, CO2, ventilation rate, occupant density and classroom size. This type of analysis involves systematically examining multiple data sets in documents, subjects, or cases to identify their similarities, differences, or patterns (Esser & Vliegenthart, 2017). This methodological approach allows researchers to evaluate frameworks and datasets compared to preestablished values or criteria sets. It also helps to understand the relationship between multiple variables and vice-versa. When applied to research contexts such as standards, policy, and norms evaluation, comparative analysis helps establish benchmarks and highlights best practices by systematically comparing key variables.

2.4.3 Document Analysis

Document Analysis is used in objectives (1, 2 and 3). In this research, the document analyses enabled a deep understanding of national and international standards and technical reports. It is also supported to evaluate the context, purpose, scope, and underlying assumption for (DQLS v1.0, DQLS v2.0, ASHRAE 62.1, CIBSE, EN-15251 and BB 99&101) revealing the motivation for each standard document. This type of analysis represents a qualitative research technique that systematically reviews the documentation and interprets the findings to bring the meaning out and establish empirical knowledge (Bowen, 2009). This analysis involves examining various materials in the form of reports, government policies, documents, and archival datasets to uncover the themes and contexts. Researchers use such approaches to corroborate findings from other sources; their publications track changes and establish historical knowledge, which is particularly valuable when direct observations or interviews prove empirical.

2.4.4 Simulation Analysis

Simulation is used in objectives 2 and 3. In this research, the simulation analysis is employed using computational modelling software (Rhino7, Grasshopper, Ladybug, Honeybee and Energy Plus) to create a reference model of primary school classroom environment across six climate zones of New Zealand. This methodological approach allows for the dynamic testing of numerous environmental impacting parameters under controlled conditions without the expense and time constraints of physical experimentation (Østergård et al., 2016). By developing parametric models incorporating various influencing parameters used in this study, temp, RH, CO2, ventilation rate, occupancy, occupants' density and classroom size, researchers can analytically predict the outcomes of environmental influencing parameters across various climatic conditions.

This research's appropriate simulation methodology workflow enabled the evaluation of the DQLS v2.0 against international standards in post-COVID-19 scenarios by modelling ventilation patterns, thermal gradients, window functioning, and CO2 concentration in different climatic zones. Such an advanced computational approach provides quantifiable evidence for determining standards' suitability and applicability for developing optimised solutions specifically calibrated to diverse climatic conditions (Gan et al., 2017). The iterative aspect of simulation analysis allows for frequent testing of multiple design interventions. It is valuable for identifying climate-responsive solutions for indoor environments that balance health safety concerns with energy efficiency and occupant comfort.

2.4.5 Descriptive Statistics

Descriptive Statistics is used in objectives (2 and 3). In this research, descriptive statistics quantify the differences between all standards findings and actual conditions of classrooms' indoor environments across six climate zones of New Zealand. It helped evaluate comparative simulation outcomes for DQLS v2.0 against international standards, which enabled the adequacy and inadequacy of New Zealand classroom typologies consideration for post-COVID-19 scenarios. This type of statistical tool comprises the mathematical steps that quantitively characterise the distributional and central properties of the data sets used in the research (Cooksey & Cooksey, 2020). This approach helps change the nature of numerical data into comprehensive theory through measures of centrality, dispersion and shape. Researchers use descriptive statistics to determine representations of numerical data sets in a precise manner, which helps identify similarities within the samples generated. Such standardised operations often enable comparative analysis or serve as a support for difficult inferential testing.

2.4.6 Thematic Analysis

Thematic Analysis is used in objective 4. In this research, the thematic analysis justifies the appropriateness of simulation methodology, comparative analysis of DQLS v2.0 against international standards and optimal design changes for post-COVID-19 classrooms. Industrial and academic feedback in coherence to validated proposed design changes and direct influencing parameters responsible for indoor environment in school classrooms. This type of analysis constitutes a qualitative methodological approach that analytically discovers, forms, and interprets patterns of themes across data through a rigorous approach (Clarke & Braun, 2017). This tool transforms narrative details into logical frameworks through iterative analysis and interpretations. Researchers use such analysis to extract latent and manifest meaning embedded in text format and repeated patterns across participants. Such theoretical viewpoints often bridge descriptive findings with theoretical value sets.

2.4.7 Mean Score Analysis

Mean Score Analysis is used in objective 4. In this research, mean score analysis enabled the quantitative assessment of industrial and academic stakeholders' agreement with simulation outcomes to establish the statistical significance of proposed optimal findings for primary school classrooms in New Zealand. This type of analysis constitutes a fundamental statistical approach that evaluates the arithmetic mean value of observed datasets to form a central viewpoint (Sullivan & Artino Jr, 2013). This approach transforms numerous individual values into a singular representative value via sum and division. Researchers use mean score analysis to determine the sum across participants' values. This identifies standardising scales within the distributions and formulates normative metrics, facilitating comparison assessment within multiple variables, parameters, groups, values, or occasions. Mean score analysis provides an arithmetic ground for many statistical approaches while offering intuitive and interpretable statistics, which state data features to various participants.

2.4.8 Literature review

Literature Review is conducted throughout the objectives (1, 2, 3, 4 and 5). A thorough exploration of the body of existing information related to the area of research acts as a cornerstone for robust research developmental constructs (Bell et al., 2022). Such exploration of the area of research not only strengthens the concepts and findings of existing studies but also guides the researcher toward identifying critical knowledge gaps in the existing area of research. The current research investigates diverse information sources related to school classroom impact on children's health and well-being in the context of indoor built environment parameters. It also examined the literature regarding COVID-19 and post-COVID-19 research in existing educational facilities to shape the current study. Later, it explored various OECD standards for indoor air quality, thermal comfort, ventilation, and carbon dioxide threshold value to produce a robust design. The modes of exploration for this study include scholarly articles, standards, documents, international guidelines, doctoral dissertations, textbooks and cohort intervention studies.

2.4.9 Pilot Study

This pilot study phase was conducted before the industrial validation phase. This phase included (three) academic staff (school designing and simulation expertise) from the School of the Built Environment, Massey University. The prime motive for conducting this pilot study was to ensure the applicability of open-ended questions and a Likert scale questionnaire with the findings for the validation phase in objective 4. Pilot studies function as feasible evaluations or instrumental validation operations before full-scale implementation (Van Teijlingen & Hundley, 2002). Such studies help identify valid methodological challenges before significant resources related to research are committed. Researchers can employ focus interview assessments or exploratory interview assessments. Such preliminary operations carry certain limitations. The researcher's perspective may be unduly affected by initial outcomes, and including such participants may contaminate the data required for the study. Using the pilot study in the current research helped-enhance the shortcomings of the open-ended questions, Likert Scale and data visualisation or readability.

2.4.10 Semi-structured Interviews

The semi-structured interviews were conducted in phase 4 (objective 4) to validate the optimal IAQ and TC design guidelines for primary school classrooms in New Zealand. The semi-structured interview (open-ended questions discussion and Likert scale questionnaire) comprises industrial validation with experts in school design, architects, building scientists, and facility managers etc. Interviews represent structured conversations or verbal discussions between the participants and researcher to express individual viewpoints on a specific area of research. While predominantly used in qualitative research, interviews can generate quantitative information (Hansen, 2021). The exchanges of viewpoints and discussions can be held by telephone or in-person to thoroughly examine the complex structure of issues. Interviews are organised into the following classifications: structured, unstructured, or semi-structured. However, the classification of structured interviews offers varying degrees of formality and interaction patterns. The pattern of question design involved a similar approach toward each participant. Structured interviews prioritise consistency and repeatability through a predetermined approach and set of questions. In contrast, unstructured interviews forgo similar questions sequentially, allowing participants greater exposure to freedom of speech. Meanwhile, semi-structured interviews balance the approaches by establishing thematic frameworks and core questions (Naz et al., 2022). While maintaining flexibility, question sequence may vary, certain inquiries might remain unaddressed, and additional questions might emerge during conversations (Fellows & Liu, 2021).

2.4.11 Sampling Method

This method was used in Phase 4 (validation) in Objective 4. The sampling technique used to determine the selection of experts with a relative background to this study and school design and air quality experts. Application of sampling methods becomes necessary when population-wide data collection proves impractical. Determining appropriate sampling approaches requires considering population parameters, resource constraints, and project-related timelines. Representative sampling techniques offer valuable advantages: well-structured data management, optimisation of resources and potential quality of data (Saunders et al., 2009). In this research, purposive sampling techniques, also known as judgemental sampling, are used. The identification of participants is based on numerous selection criteria. It includes architects, building assessors, building data analysts and scientists, directors, BIM modellers and lecturers with a minimum of 5 years of experience to 25 years of experience from the New Zealand industrial and academic area who have previously worked with school design, based on their knowledge depth and potential contribution value (Rai & Thapa, 2015). Although numerous emails and invitations to participate were sent to individual designers and shared on social media platforms such as LinkedIn, we also contacted designers via professional bodies such as the New Zealand Institute of Architects (NZIA), the New Zealand Chartered Institute of Building (NZIOB), etc to achieve adequate response rates. Implementing convenience and expertise-based selection approaches introduces certain methodological constraints that merit acknowledgement.

2.4.12 Reliability and Validity

To translate the research findings into the practical mode of application, rigorous evaluation of their quality is essential (Noble & Smith, 2015). Two pivotal metrics for judging the research merits are reliability and validity. Validity is expressed by the extent to which the research findings accurately reflect the investigations. Conversely, reliability pertains to the consistency of the area of research tools used, ensuring that repeated values under a similar approach can yield comparable outcomes (Heale & Twycross, 2015).

According to (Saunders et al., 2009), validity encompasses three dimensions:

a. Measurement Validity: Measurement validity, also called construct validity, describes the extent to which measurement indicators used in the study capture theoretical concepts to what extent they claim to measure or the constructs being studied.
b. Internal Validity: It specifically deals with the certainty of research tools applied accurately to capture the intended constructs under the area of research and determines cause-effect connections to reduce the chance for varied interpretation of outcomes.
c. External Validity: It focuses on the research findings demonstrating applicability beyond the original context to a comparable environment in the area of research.

Hence, all the above validity dimensions collectively serve to strengthen the accuracy of the research. While reliability ensures stability during the measuring procedure. Together, both reliability and validity serve to enhance the credibility and trustworthiness of the research findings. For this study area, the research problem statement is identified from the literature reviews, document analysis, and content analysis of scholarly articles and international standards from OECD countries.

To ensure the reliability of the simulation outcomes, the classroom reference design model developed in Rhino 7 and the Grasshopper script for parameters were tested and run multiple times to identify the potential bugs and determine the marginal error across both classroom typologies in six climate zones of New Zealand. Each multi-criteria optimisation variable was calculated for national and international standards. In simulation studies, the marginal error of ± 1 to 15% is considered highly reliable for indoor building environmental calibration studies (Hong et al., 2000; Crawley et al., 2008; Coakley et al., 2014; Attia et al., 2012). Both classroom typologies were carefully calibrated, and model comprehension in the script was run and tested five times, with results consistently showing marginal variation of ±5 to 10% across all the interactions for each multi-criteria optimisation variable for national and international standards. This consistency of outcomes across repeated simulations demonstrates the reliability of the research findings. Furthermore, the simulation methodology presents all input parameters comprehensively, with constant values based on published scholarly simulation research, ensuring if the script were to be run for other classroom typologies by different researchers, followed with careful calibration and similar protocols for IAQ and TC parameters, the findings would be comparable with the current research. This repeatability further reinforces the reliability of the current research outcomes.

The internal validity of this research simulation methodology is established through a careful selection of validated simulation software(Rhino 7), followed by a critical consideration of direct influencing parameters for IAQ and TC in school classrooms. The core simulation environment employs Rhino 7 software for designing the reference model of school classrooms. It is integrated with the Grasshopper algorithmic plugin and offers a parametric modelling framework with established validation in building performance research. With the help of a literature review, the parameters selected for IAQ and TC affecting the indoor classroom environment were prioritised for parametric modelling, as discussed in Chapter 5, section 5.2, to ensure the focused evaluation of selected variables. The simulation methodology is strengthened and internally validated by integrated environmental analysis plugins (ladybug and honeybee tools) (Attia et al., 2012; Elshafei et al., 2017; Azizpour et al., 2013). The ladybug tools enhance reliability through its capacity to conduct detailed climatic analysis and weather data integration and interpretation; Honeybee facilitates, in conjunction with Energy Plus and Open FOAM, to conduct detailed thermal, ventilation, energy and daylight analysis. Hence, such an integrated software ecosystem creates a reliable measurement practice with consistent, reproducible simulation results and findings, which supports the internal validity of software selection and parameters used in the research assessment in the context of the indoor environment.

To establish external validity for the area of research, industrial and academic experts with significant years of experience with school design were engaged in semi-structured interviews. The preparation of open-ended questions and a Likert scale questionnaire for semi-structured interviews involved the expertise of supervisors. The external validity of the findings involved open-ended questions in reviewing the appropriateness of simulation methodology, comparative analysis of international standards used against DQLS v2.0 and optimal design guidelines for IAQ and TC for New Zealand primary school classrooms. The Likert scale questionnaire for external validity enabled the industrial and academic stakeholders' feedback to structure validation outcomes. The Likert scale questionnaire directly addressed the measurable IAQ and TC parameters and optimal design outcomes used in the research. The Likert scale questionnaire was particularly designed to gauge industrial and academic stakeholders' points of view toward the current IAQ and TC functioning within the New Zealand classroom typologies across six climate zones and the applicability and feasibility of optimal design changes for post-covid 19 scenarios in primary school classrooms of New Zealand. Moreover, a pilot run of semi-structured interviews was also conducted in-house with academic staff to identify and resolve potential issues with open-ended questions and a Likert scale questionnaire before deploying the full survey application. This methodical validation approach strengthened the research design's robustness and enhanced the credibility of subsequent findings.

2.5 Research Ethics

This research considered various ethical considerations. As a part of ethical consideration, various influenced decisions were made. For instance, during COVID-19, ethical consent led to a change in the scope of the study. Earlier, it involved visiting schools to connect with primary school class teachers and principals to collect indoor classroom occupants' behavioural information and classroom indoor environment-related information. Later, the study adopted the simulation methodology to neglect human interactions (children and adults) to maintain the ethical code of conduct and research robustness. The Massey library and staff services also helped purchase the international standards, which were unavailable for this study online. The right procedure to purchase (standards) was followed via research funds to maintain ethical conduct, and after using the standards, they were safely returned to Massey Library without any damage or loss. The purchase of the licensed simulation software (Rhino 7) was also followed by the School of Built Environment, Post-Graduate lead, Admin and finance department people. All the simulations were conducted with the Massey University computer system (IT No. 090020) specifically designed to run simulation software with high specs requirements. The simulation parameters used in the study were based on international standards. Ethical considerations play a significant role for researchers throughout the research process. A researcher must completely follow all the ethical dimensions of their work, particularly with participants' involvement and data acquisition stages. Research ethics encompass behavioural guidelines governing interactions with study participants that direct information-gathering procedures (Saunders et al., 2009). These guidelines derive from societal behavioural expectations and philosophical underpinnings of ethical research practice. Variations within individualistic conduct through contexts and contrasting philosophical frameworks result in diverse points of view regarding appropriate ethical techniques. This diversity has necessitated the development of formalised ethical frameworks incorporating these various elements.

This research adheres to the ethical frameworks established by the Massey University Human Ethics Committee (MUHEC). Through the process, all the necessary ethical considerations were observed closely with the research. Given the participant's involvement in the research process for the valuable data collection phase, MUHEC requested formal authorisation and subsequently granted it. The approval assigned ethics number for this study consideration under low-risk classification is **4000027845.** MUHEC's core ethical principles are presented in Table 2.3

Table 2.4: Ethical Core Considerations-Saunder et al., 2009

Ethical Principles	Implementation Approach
Honesty and Neutrality	Truthfulness and Openness
Respect for person	Individuals are treated with dignity, autonomy and respect
Minimisation of harm	Research designed to prevent potential negative consequences
Informed consents	Comprehensive information and voluntary participation endured
Privacy and Confidentiality	Protection of data measures, identify safeguards maintained

Social and Cultural sensitivity	Recognition of diverse backgrounds, appropriate accommodation as per individual need

Ethical considerations played a vital role in the validation phase. To direct the informed consent needs, every participant received a Participants Information Sheet and the Consent form before the meeting scheduled to get an idea about the research background. All the participants were formally accorded appropriate respect and dignity throughout the research process. Collected data and information for each participant was securely stored on a Massey University hard drive with access restricted exclusively to the primary researcher and Supervisory team. The findings from the simulations were presented, and the researcher did not lead the questions; rather, each participant had enough time to review them independently to discuss the findings with openness and honesty. Such ethical principles also helped with gaining the expert's feedback to enhance future recommendations. The identity of industry experts was kept anonymous and the semi-structured interview conducted was one on one.

Chapter 3 Prologue

This chapter addresses a fundamental question: are New Zealand's indoor air quality and thermal comfort standards for primary school classrooms adequate to protect children's health and support their learning? To answer this, the chapter examines the Designing Quality Learning Spaces (DQLS) document, the Ministry of Education's official guideline that sets design requirements for school buildings across the country.

The chapter compares two versions of this critical document: Version 1.0 (released in 2017) and Version 2.0 (released in 2022). This comparison reveals what has changed, what has improved, and where gaps remain in New Zealand's approach to creating healthy learning environments. The analysis focuses on measurable parameters that directly affect children's well-being carbon dioxide concentration, ventilation rates, indoor temperature, relative humidity, and window-to-wall ratios.

Readers will find three key components in this chapter. First, a literature review establishing why indoor air quality and thermal comfort matter for children's health, attendance, and academic performance, with particular attention to New Zealand's context where 90% of schools rely on natural ventilation. Second, a detailed comparison of the technical requirements between DQLS versions 1.0 and 2.0, presented in accessible tables that highlight specific changes in standards. Third, a discussion of what these changes mean for school design practice and where further improvements are needed, particularly regarding occupant density and space allocation.

This chapter serves as the foundation for the research that follows, establishing the baseline standards against which subsequent chapters will evaluate classroom performance through simulation and expert validation. Understanding these guidelines is essential because they shape every new school building and renovation project in New Zealand, directly affecting hundreds of thousands of students' daily learning environments.

3. A Review of Indoor Air Quality and Thermal Comfort Guidelines for New Zealand Primary School Classrooms: A Comparison of the DQLS document (Old Versus New)

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Abstract

Multiple health-related illnesses are associated with poor air quality in schools, especially for young children. Research shows that children aged 5-8 years are highly susceptible to indoor air pollution due to their smaller body mass index. Apart from their homes, schools are a common source of inhaled indoor air pollution and have been linked to children's impaired performance. In New Zealand, the Ministry of Education, Designing Quality Learning Spaces (DQLS) guideline provides performance requirements for learning spaces in new and older school buildings. The DQLS guidelines focus on specific design aspects that target learning spaces' usability, ventilation, heating & cooling, daylight, and acoustic design. It aims to provide a standard code of practice that enhances Indoor Air Quality (IAQ), ventilation, and thermal comfort in school buildings across the country. Therefore, this paper objective is to compare two versions of the Designing Quality Learning Spaces document (DQLS), an integral part of the Ministry of Education, New Zealand. In order to achieve this objective, a critical comparison has been conducted for IAQ and Thermal comfort to older and latest versions of the DQLS document using content analysis. The six steps to review the study are clearly stated

in the methodology. There has been a significant change between the 2017 and 2022 versions. The change requires a critical review to ascertain the appropriateness of differences made. The review highlights the appropriate changes incorporated and their potential impact on the design and management of the IAQ and Thermal Comfort in New Zealand Classrooms. This study will offer valuable insights and recommendations toward the practicality of the mandatory requirements in the DQLS version 2.0, 2022, by comparing it with the DQLS version 1.0, 2017. The outcome of this study will be helpful for school building designers and architects in understanding and implementing the new IAQ, Ventilation, and Thermal Comfort requirements for designing schools across the country. Thus, ensuring the provision of optimal IAQ, ventilation, and thermal comfort requirements for school children.

Key Words: Children, IAQ, New Zealand Schools, Thermal Comfort, Ventilation, and Vulnerable Population.

3.1 Introduction

The good quality of the indoor air environment in a school classroom is essential for children. It offers an indoor space with fresh air, which is vital for their health and well-being. However, the Environmental Protection Agency of the United States of America (USEPA) has listed IAQ within an indoor environment as a top concern with context to respiratory and ill health-related issues (US EPA, 1993; Loh & Andamon, 2017). Studies in school premises examining IAQ have been a popular concern for years. The adverse effects of poor IAQ have been extensively studied in past works. For instance, Ivosevic et al. (2020) showed that the impact of poor IAQ is reaching far beyond children's health. Poor IAQ impacts children's health and lowers their learning abilities (Ivosevic et al.2020). Korsavi et al. (2020) noted that IAQ in school environments is considered one of the crucial factors which impact children's health and well-being, and further, it costs their academic results.

Children are found to spend approximately 10 to 12 % of their living time within the school classroom (Mendell & Heath, 2005). Henceforth, it becomes crucial for governing bodies and school authorities to ensure the IAQ prevalent in the classroom is well maintained for children (Chatzidiakou et al., 2015). Monitoring IAQ in a school classroom is mainly done by assessing the concentration of carbon dioxide and ventilation rates. The physics shows that higher levels of carbon dioxide in the indoor environment are directly proportional to lower ventilation rates. Thus, both the concentration of carbon dioxide and ventilation rates are considered significant proxies or indicators for checking the quality of indoor air (Chatzidiakou et al., 2015; Bako – Biro et al., 2012).

The concentration of carbon dioxide above 1000 ppm indicates inadequate ventilation rates within the indoor environment. High carbon dioxide levels are associated with an unpleasant indoor atmosphere, which can negatively impact indoor air quality (Annesi-Maesano et al., 2013). Inadequate ventilation hinders the proper exchange of fresh air, accumulating carbon dioxide and potentially other pollutants. This affects the comfort of the individuals present in the space and indicates a potential decline in the indoor air quality, which is associated with an unpleasant environment (Annesi- Maesano et al., 2013). Poor IAQ creates an unhealthy indoor environment for children, which is also considered a significant cause of the development of chronic illnesses related to the respiratory tract in children (Taptiklis and Phipps, 2017).

A justifiable gap exists in ascertaining the changes to IAQ and thermal comfort standards amendments in DQLS version 2.0, which requires critical comparison to address the possible scenarios with context to Indoor air quality and thermal comfort in New Zealand classrooms. Therefore, this paper's objective is to compare two versions of the Designing Quality Learning Spaces document (DQLS), an integral part of the Ministry of Education, New Zealand. The document offers the technical requirements to various industry people like architects, designers, and engineers to model the design of the school, which is appropriate for the intended use. Technical guidance is provided at the managerial level for those who intend to work on projects related to school properties. The significance of this study is to ascertain the importance of the remarkable improvements made between the two versions of the DQLS document towards designing schools to offer quality learning environments for children.

The design requirement expressed in the DQLS document applies to all the school dwellings to be “Newly – Built” or “ Existing”.

3.2 Literature Review

3.2.1 IAQ, Schools, and Student Performance

Studies related to health have shown vast evidence of environmental agents like thermal discomfort (high temperatures) and air pollution impacting and challenging individuals' physical and mental health. Air pollution agents like fine particulate matter and ozone are directly associated with the development of cardio and respiratory illness in the human body (Liu et al., 2019). A scientific study by Taylor et al. (2015) shows that long-term exposure to air pollution can cause fatal damage to the human neurological system, leading to cognitive disability, stroke attacks, fatigue, and depression in the adult population. The abovementioned impacts are likely to cause more detrimental effects among young children due to the lack of fully grown body parts and systems. Hence, children are more vulnerable and susceptible to air pollution as their nervous system, immune system, and respiratory system are in the developing stage, also due to a higher percentage of breathing than adults (Makri et al., 2004).

IAQ in school is commonly found to be poor due to the higher number of occupants and inadequate ventilation rates, resulting in thermal discomfort. Similarly, classrooms are usually considered overcrowded and vary in temperature (high temperature) and lower airflow (Korsavi et al., 2020). Poor IAQ in school buildings is a combined result of the building design, maintenance, and occupancy-related factors (Spengler & Chen, 2000). Studies conducted in epidemiology and neuroscience with context to cognitive ability and children have shown significant evidence that most schools do not maintain carbon dioxide concentration below 1000 ppm, impacting children's cognitive performance (Fisk, 2017).

Coley & Beisteiner, (2002) state that a higher number of children in the classroom is directly associated with high carbon dioxide levels. Children aged between 5 to 9 years tend to produce around 14 litres of carbon dioxide each hour in a regular breathing routine. Various international organising bodies worldwide have made a tolerance limit for the maximum percentage of carbon dioxide in the classroom, which should be approximately 1500 ppm. Looking at the young children aged between 5 to 9 years, their tolerance limit is anticipated to be achieved sooner to 1000 ppm. Additionally, after a specific limit depending upon rates of ventilation and the number of occupancy, the movement of the air becomes stagnant, which can cause nausea, severe headache, concentration issues, a problem with vision, fatigue, and other severe problem in young children (Poscia et al., 2014).

Numerous studies have shown a significant association between enhancing the quality of indoor air in school classrooms improves student performance in academic results and well-being (Porta et al., 2016; Brabhukumr et al., 2020; Harris et al., 2015; Pujol et al., 2016; Chiu et al., 2013). A study conducted in the State of America involving the participation of 100 schools stated that by improving ventilation rates, significant results were observed in student academic records within mathematics and reading abilities (Haverinen-Shaughnessy et al., 2011). In another study conducted in Austria, which involved the participation of around 400 children, the findings observed lower cognitive abilities due to a higher percentage of carbon dioxide and particulate matter (Hutter et al., 2013). Similarly, in Scotland's study, which involved the participation of 60 schools, the finding stated that a higher level of carbon dioxide presence was associated with absenteeism and lower academic results in reading, writing, and mathematics tests (Gaihre et al., 2014). Additionally, in Portugal, which involved the participation of 50 primary schools, the finding from the study stated that a higher percentage of carbon dioxide was associated with less concentration of attention in children within a classroom (Twardella et al., 2012).

Likewise, in other Western countries, children in New Zealand are expected to spend the majority of their time within an indoor environment, i.e., a school classroom. Also, which gives the classroom considerable exposure to them with context to IAQ and its pollutant. Severe respiratory conditions like asthma and high absenteeism rates are common in New Zealand (Bennett et al., 2019). Exposure to continuous poor IAQ is responsible for worsening the da symptoms at a high rate (MacIntyre et al., 2014). Indoor and outdoor sources impact the quality of the air in classrooms, and research has shown that indoor particulate matter (PM) concentrations are closely connected with outside ones. This is concerning since many schools and day-care centres are situated on major highways with high levels of traffic-related air pollution, which elevates during schooling hours (Raysoni et al., 2011; Sunyer et al., 2015). Similar to other Western countries' studies, enhancing ventilation rates in New Zealand school classrooms has brought significant attention to improving the children's well-being and learning abilities and less the percentage of school absenteeism (de Gennaro et al., 2014).

The majority of schools in New Zealand, approximately 90 %, are reliant on natural sources of ventilation, which is by opening doors and windows (McIntosh et al., 2011). The Ministry of Education, New Zealand, is the governing body which proposes regulation and design requirements for school classrooms. In 2017, MOE established the average and maximum threshold for the concentration of carbon dioxide should not go beyond 1500 ppm to 3000 ppm during peak hours. The range was established to understand indoor air quality and ventilation rates for newly built and existing schools in the state for upgrades (Ministry of Education, 2017a).

The governing body of New Zealand, the Ministry of Education (MOE), holds a majority of state schools worth around NZD 30 billion (Hipkins, 2020). It is anticipated that more than two-thirds per cent of total students attend a state school, approximately 11 per cent attend integrated school and 4 per cent attend privately owned schools. Multiple schools and dwelling initiatives over the past 30 years can be attributed, at least partly, to the poor condition of New Zealand's educational facilities. During these years, schools that underwent renovation projects also experienced problems with leaky construction in dwellings due to weak design and construction materials available. Following multiple years of neglect for educational facilities, a significant development plan for modern or upgraded classroom design is underway in many New Zealand schools. These classrooms are supposed to be contemporary or adaptable learning spaces. Innovative learning surroundings, creative learning spaces, flexible learning, and quality learning environments have been used to describe newly constructed or upgraded classrooms (Benade 2017).

The problem associated with quality and aesthetics in New Zealand school buildings has already been outlined in the document released by the Ministry of Education named "The School Property Guide" (Ministry Of Education, 2015). The official document provides recommendations for procedure, capacity or area, and budget. Furthermore, new and all other ongoing upgrading projects related to school dwellings must be certified by the Ministry of Education and must go under a design review procedure followed by both the Ministry of Education and the School Property Guide document. The "School Property Guide" document specifies space criteria for classrooms as 75 m2 for primary school classrooms and 70 m2 for secondary school classrooms (Ministry of Education, 2019). However, designing educational spaces for better quality requires a 3 to 4 m^2 minimum space between children to achieve healthy Indoor Environmental Quality. In addition, the present norm-keeping cost and salary ratio allows a single teacher for 30 children. Henceforth, to achieve healthy indoor environmental quality in a better/quality learning classroom, the ideal area with a single teacher and 30 students should be around 90 to 120 m^2 instead of 70 to 78 m^2 (Ministry of Education, 2016).

3.2.2 IAQ & Thermal Comfort (IAQ & TC) importance for designing quality learning spaces

Previous studies have already shown enough robust evidence that good IAQ & TC supports children's learning outcomes and helps improve their health and well-being (Barrett et al., 2015; Wall, 2016; Ackley et al., 2017; Ackley, 2021). Good indoor quality within educational facilities or spaces not only offers support to the teacher but also provides help to learners efficiently toward success. Poorly ventilated indoor areas can create undesired thermal discomfort and high level of carbon dioxide, which can further lead to tiredness and often feeling sleepy (Ackley, 2021b). Pollution in the indoor environment is commonly found to be noxious and can create irritation within the eyes and nose leading to itchiness, which can interfere with learning tasks. Young children in school premises are considered more susceptible to indoor air contaminants than adults as they tend to breathe more air, and their body parts are actively developing. Due to such differences in body parts and higher metabolism rates, children are also considered to be quite sensitive to higher indoor temperatures. Children, compared to adults, tend to have more physical activities, making them sensitive to high temperatures. Thus, children are anticipated to stay more comfortable in a few lower temperatures within the indoor spaces.

The major purposes behind setting out requirements for IAQ&TC for designing quality learning spaces include designing spaces such as indoor learning environments which are thermally comfortable in support of different learning and teaching techniques and traditions. To set out the compulsory minimum threshold limit to achieve quality indoor learning spaces. To set out the basic evaluation requirement for IAQ & TC with context to the project designing phase and Post Occupancy Evaluation (POEs). To assist the designing and modelling of schools by emphasising the cost value model, with pressing attention toward enhancing academic results (MOE, 2022).

The New Zealand Ministry of Education is committed to providing healthy classrooms by enhancing the IAQ and thermal comfort. Looking at the compounded nature of the classroom, the indoor environmental quality (IEQ) of such complex spaces requires greater detailed attention. The designers must ensure that during the design stage of the classroom, the requirement set out in the DQLS document is to be applied together for IAQ & TC along with acoustics and vision/lighting requirements in parallel. However, indoor environmental quality (IEQ) is considered a system in commissioning the entire building quality, which comprises different variables: IAQ, thermal comfort, acoustics, and lightning. These variables should be evaluated throughout the process of designing to ensure comfort. A complete strategy is required, and every indoor environmental quality variable should be changed after first considering its impact on the others (MOE, 2022). This study compares the standard of IAQ and TC for designing quality learning spaces as main objectives with two different versions of the DQLS document.

3.3 Methodology

The study opts a qualitative method using content analysis by comparing measurable variables responsible for Indoor air quality, Ventilation and Thermal comfort evaluation within an indoor environment. The measurable variables opted for this study include carbon dioxide concentration, ventilation rates, indoor temperature, relative humidity, and window-to-wall ratio, as the above variables are closely interconnected (DQLS, 2022). The data collected for this study to perform content analysis includes two sets of Designing Quality Learning Spaces documents. The DQLS document versions 1.0 and 2.0 were released in 2017 and 2022, respectively.

The literature review related to schools, children, IAQ, ventilation, thermal comfort, academic result, and well-being were reviewed using online database resources like Google Scholar, Massey Library, and PubMed. Abstracts and titles were read thoroughly to understand the relativity of the available online source to the present study. Hence, after reviewing the abstract, titles and keywords, the relative journal articles and other resources opted to support the finding for this study. The steps undertaken to perform this study are stipulated below in Figure 3.1.

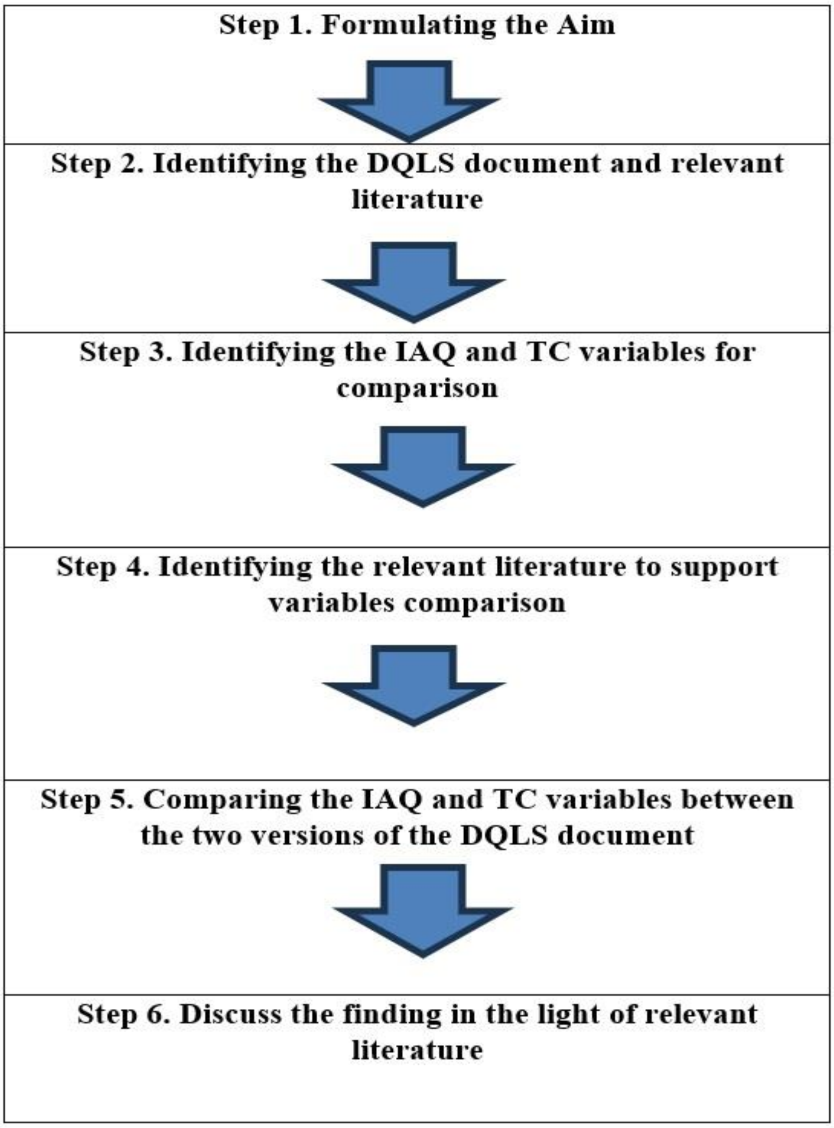

Figure 3.1: Research method flow-chart

3.4 Comparison of old versus new Designing Quality Learning Spaces (DQLS Document)

The DQLS document aims to ensure that indoor air quality and thermal comfort within the New Zealand educational spaces support good academic results. It is done by establishing the minimum standards and addressing suggestions while constructing or renovating school dwellings. The DQLS document has undergone a substantial upgrade since its first release. In 2007, in collaboration with the Building Research Association of New Zealand (BRANZ), the document was released in two different sections, i.e., Designing Quality Learning Spaces – Heating and Insulation, and Ventilation and IAQ. In 2017, the Ministry of Education New Zealand amalgamated the first release of the document in sections into one document named – Designing Quality Learning Spaces: IAQ and Thermal Comfort (Version 1.0). The significant changes incorporated in version 1.0, released in the year 2017, include a recommendation to present teaching practices and adaptable learning practices to the designed space. The upgraded information in the document marked minimum criteria as "Mandatory" and "Recommendation", which solely align/target industry people such as architects, engineers and designers involved with educational construction practices to newly built or upgrade designs. In 2022, the Ministry of Education New Zealand released the latest version, 2.0 for the DQLS document, adding further changes to the minimum criteria for "Mandatory" and "Recommendation" for designing quality learning spaces stronger and to better-complying industry standards and recent construction reviews.

The latest version, 2.0, presses the strengthened mandatory requirements to support the Ministry of Education's objective "School Property Strategy 2030" program. The objective is to provide quality educational spaces for learning and teaching practices and keep well-being in focus simultaneously for all individuals present on school premises. The Ministry of Education in New Zealand holds one of the largest real estate properties, with over 15,000 properties, over 35,000 educational spots, and around 2,100 teaching institutions. The designing and upgrading of educational learning spaces are commissioned through a variety of procedures by both national and regional governing levels (Ministry Of Education, 2022). Tables 3.1 and 3.2 below present the minimum to maximum requirements for IAQ, ventilation, and thermal comfort between the two sets of DQLS documents published in 2017 and 2022, with individual upgrades to previous versions.

Table 3.1: IAQ, Thermal Comfort and Ventilation- DQLS, 2017

Season	Summer	Winter
	Minimum	Maximum
Carbon dioxide	1000 -1500 ppm (Average)	3000 ppm
Outdoor air supply (ACPH)	2.5 ACPH – 5 ACPH	0.5 ACPH – 2 ACPH
Outdoor air supply (L/s/p)	6 l/s/p – 8 l/s/p	1.5 l/s/p – 5 l/s/p
Ventilation Effectiveness	Ideally achievable (Average)	Poor ventilation
Subjective Response	Light Odor	Odors, Stuffiness, Headaches, and Fatigue
Student Performance (percentage)	Averagely close to 100%	Minimizes by 5% to 10%
Absenteeism (percentage)	Close to 5%	Increase to 15 %
Indoor Temperature	18℃ - 28℃	18℃ - 25℃
Relative Humidity	--------------	
Window to Wall	30% to 50%	

The mandatory minimum & maximum allowable criteria for IAQ, Ventilation and Thermal Comfort for New Zealand classroom depicted in Table 3.1 and Table 3.2 show significant changes between version 1.0 and 2.0. Looking at carbon dioxide concentration and ventilation range for DQLS, 2017, the minimum range lies between 1000 ppm and 1500 ppm, and the maximum permissible range is 3000 ppm. In contrast, in DQLS, 2022, the minimum range has been minimized to 800 ppm to 1250 ppm and the maximum permissible range to 2000 ppm. According to Wargocki et al. (2020), the finding states around 12 % improvement in performance and a 2 % improvement in accuracy was observed in children when the average minimum concentration of carbon dioxide was decreased from 2000 ppm to 900 ppm. Keeping attendance as a positive indication for healthy IAQ in the classroom, a 2.5 % improvement was observed when carbon dioxide ranges below 1000 ppm daily. Additionally, for the supply of outdoor air (l/s/p), DQLS, 2017 range between 6 l/s/p to 8 l/s/p, whereas in DQLS, 2022, the supply of outdoor air has been increased to 8 l/s/p to 12 l/s/p. The range for 10 l/s/p of outdoor air supply is closely associated with the range of carbon dioxide below 1000 ppm (Wargocki et al., 2020).

Table 3.2: IAQ, Thermal Comfort and Ventilation - DQLS, 2022

Season	Summer			Winter
	Minimum			Maximum
	On-Demand		Average	
Carbon dioxide	800ppmm	-	1250 ppm	2000ppm
Outdoor air supply (ACPH)	3 ACPH	-	7.5 ACPH	2 ACPH
Outdoor air supply (L/s/p)	8 l/s/p	-	12 l/s/p	3.5 l/s/p – 4 l/s/p
Ventilation Effectiveness	Well-ventilated to an ideal range			Poor ventilation
Subjective Response	Close to supply of fresh air			Odour and stuffiness
Student Performance (percentage)	110 % to 100 %			Slightly lower to 95 %
Absenteeism (percentage)	Less than 5 %			Increase to 10%
Indoor Temperature	19°C to 25°C (No more than 40 Occupied hours)			
Relative Humidity	Should by 35 % to 70 %			
Window-to-Wall Ratio	25 % to 35% (To reduce Overheating and allow more daylight)			

Research conducted in primary schools in California found that increasing the ventilation rates by 1 l/s/p improved academic results (Mendell et al., 2013). Another study stated that doubling the ventilation rates in primary school classrooms improved children's performance by 14 % (Wargocki & Wyon, 2013). Moreover, 10 % less spread of illness is anticipated when the air supply is doubled in the classroom (Fisk et al., 2017; Fisk et al., 2003). The indoor temperature (Classroom) range for DQLS 2017 is set between 18°C to 25°C. It is a mandatory requirement that during the occupied hours, the internal temperature should not go beyond two threshold limits, i.e., 25°C and 28°C. In addition, to the above statement, the difference between indoor and outdoor temperature during occupied hours should not exceed 5°C. In contrast, to DQLS, 2022, the minimum requirement for indoor temperature should be 19°C (+/-1°C), and the maximum permissible indoor temperature should be 25°C for no more than 40 Occupied hours. Previous studies conducted in a classroom with context to thermal comfort and children's health, well- and academic performance have shown that with every 1°C fall within the indoor temperature resulted in a positive by 2 to 4 per cent in children's academic results (Wargocki & Wyon, 2007; Wargocki & Wyon, 2013; Katafygiotou & Serghides, 2014; Zhang de Dear & Hancock, 2019). However, with context to the range for relative humidity in DQLS, 2017 has not exactly been mentioned, but in DQLS, 2022, the RH range should be maintained within 35% to 70%. According to (Jin et al., 2017; Jing et al., 2013), the percentage of RH does not directly impact thermal discomfort. However, its effects get intense with higher differences between indoor and outdoor temperatures and higher metabolic rates.

3.5 Discussion

The current discussion section gives insightful information or findings about the comparative analysis conducted for versions 1.0 and 2.0 of DQLS documents. The section will provide information on the improvement of the DQLS document and the gaps or backlog.

Designing Quality Learning Spaces, Version 1.0 (2017): Aims to ensure learning spaces in New Zealand support offering quality outcomes by improving IAQ and TC. Version 1.0 typically focuses on the usability of learning space and its impact on academic outcomes, whereas Version 2.0 includes enhancement with education results, maintaining health and well–being.

Designing Quality Learning Spaces, Version 2.0 (2022): The main objective is to ensure learning spaces in New Zealand support academic outcomes and improve the health and well-being of every individual present within the school premises. Moreover, the minimum necessary requirement in Version 2.0 is established in response to best practices and, in particular, to MOE's requirements. Still, it is also stated that the current Version 2.0 DQLS document design does not address each possible case. In addition, it provides the solution to the problem on behalf of recent research, technology, innovation, new methods, and feedback to address common issues.

Overall, both document has their advantage and disadvantages with context to published time. However, according to the study point of view, DQLS Version 1.0 solely focused on IAQ, Ventilation and Thermal Comfort, whereas DQLS Version 2.0 understand that strengthening standards will work. Still, it has to be a holistic approach which addresses overall performance. Additional new information or changes incorporated in Version 2.0 is an understanding of the importance of indoor environmental quality. However, IAQ, ventilation and thermal comfort are three sub-sections of IEQ as a holistic model for a dwelling. Furthermore, version 2.0 holds a sub-section in the document, which provides significant information about adequate ventilation rates and minimizing the aerial pathogen and COVID-19. In version 2.0, there has been a significant change with window to wall ratio to version 1.0, as DQLS, 2022 focuses on reducing overheating and allowing more daylight. Both version 1.0 and 2.0 stress following natural means of ventilation in New Zealand schools, although there is a requirement for adopting mechanical ventilation.

3.6 Conclusion

After a thorough review of both the DQLS documents and other relevant online data sources, including a comprehensive scientific literature review, the authors of the study have arrived at the following conclusion that the minimum requirements and recommendations stated in DQLS documents align with international guidelines followed by different countries to enhance the IAQ, ventilation and thermal comfort standards for school dwellings. The DQLS document developed used Thermal Comfort: ASHRAE 55, (2017) & CIBSE TM52 and Ventilation: UK Building Bulletin 101 (Ventilation for school building). The minimum airflow was developed from NZS 4303:1990 in mechanically ventilated school classrooms. The latest version, 2.0, released in 2022, has significantly enhanced the minimum mandatory requirement for the concentration of carbon dioxide, air flow rates, indoor temperature, and window-to-wall ratio. However, neither version 1.0 nor version 2.0 have provided specific criteria for occupant density and space. However, from a literature point of view, it is found that in New Zealand primary school classrooms, the maximum number of occupancy for children is 30 with a single teacher for a total space area of 70 to 75 m2. Moreover, following the OECD country's guidelines for better holistically enhancing the IEQ within indoor educational spaces, the minimum occupant density should be around 3 – 4 m2, ideally making a total classroom learning area around 90 – 120 m2.

The novelty of this research includes critiquing the DQLS documents, which have never been done before. Also, the documents are an integral part of the governing entity of New Zealand, the Ministry of Education and the research conducted is an educational perspective to understand the importance of IAQ and Thermal Comfort standards, thus making the outcome with an unbiased point of view. However, the study compared the two DQLS documents with context to IAQ and TC standards for healthy indoor environments in New Zealand classrooms. The study is limited to the New Zealand context, which can be expanded when compared to other Western countries for IAQ and TC classroom standards. Another limitation is the methodology used in this study. Future studies can incorporate a mixed-method approach using both qualitative and quantitative analysis.

Chapter 4 Prologue

Building upon Chapter 3's examination of New Zealand's DQLS standards, this chapter places these guidelines within a broader international context by comparing them against standards from economically and climatically similar OECD countries. The fundamental question driving this comparison is: how do New Zealand's indoor air quality and thermal comfort standards compare to proven international benchmarks, and where do opportunities for improvement exist?

This chapter examines standards from five major frameworks: ASHRAE 62.1 (United States), CIBSE TM57 (United Kingdom), WHO Air Quality Guidelines (global), EN-15251 (European Union), and Building Bulletins 99 and 101 (United Kingdom). These international standards are compared against New Zealand's DQLS Version 2.0 across six critical parameters: temperature ranges, carbon dioxide concentration limits, ventilation rates, classroom size, occupancy numbers, and occupant density. Each parameter has a direct influence on children's health, cognitive performance, and learning outcomes.

Readers will encounter three main components in this chapter. First, a background section establishes why international comparison matters, exploring how factors such as carbon dioxide and ventilation rates affect children's academic performance and health, with particular attention to New Zealand's unique context, where most schools rely on natural ventilation. Second, a detailed methodology explaining the selection criteria for comparison standards and the rationale behind choosing specific parameters that interconnect to determine indoor environmental quality. Third, comprehensive findings and discussion revealing where New Zealand's standards align with international best practices and, importantly, where gaps exist, particularly concerning maximum carbon dioxide thresholds and occupant density specifications.

This comparative analysis serves a critical purpose: identifying evidence-based improvements that could strengthen New Zealand's approach to creating healthy learning environments. Understanding these international benchmarks becomes essential as the research progresses toward developing optimal design solutions in subsequent chapters, ensuring recommendations align with globally recognized standards while addressing New Zealand's specific climatic and educational needs.

4. Comparative Analysis of Indoor Air Quality and Thermal Comfort Standards in School Buildings across New Zealand with Other OECD Countries

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Abstract

COVID-19 has improved awareness of the importance of appropriate indoor air quality (IAQ) in indoor spaces, particularly in classrooms where children are expected to learn. Research has shown that poor IAQ and temperature levels affect the cognitive performance of children. In this paper, we critically compare IAQ standards for New Zealand's Designing Quality Learning Spaces (DQLS Document) against international benchmarks from the Organization for Economic Co-operation and Development (OECD) countries, including ASHRAE 62.1, CIBSE TM57, EN-15251, WHO AQGs, and Building Bulletins 99 and 101. The aim was to ascertain the robustness of New Zealand's DQLS document, identify areas of superiority, and recommend the required improvement for appropriate IAQ and thermal comfort in classrooms. This comparison review focuses on IAQ parameters: CO2 levels, temperature, ventilation rates, room size, occupant density, and occupancy rates. The findings illuminate a slight lag in New Zealand's DQLS standards compared to her international counterparts. For instance, while New Zealand's standards align closely with WHO standards for IAQ concerning temperature and ventilation rates, the recommended CO2 range appears slightly inadequate (800 to 2000 ppm) along with occupancy and classroom size for effectively controlling classroom pollutant growth. This paper emphasises the need to align New Zealand's IAQ and thermal comfort standards with optimal OECD benchmarks. The identified disparities present opportunities for improving learning spaces in terms of CO2 concentration, size of classroom, and occupant density in schools in New Zealand to meet globally recognised standards, ultimately creating a healthier and more conducive learning environment.

Keywords: school; indoor air quality; thermal comfort; OECD countries; performance; health

4.1 Introduction

Ensuring Healthy Air Quality is important in school indoor environments to provide conducive conditions for students and teachers (Sadrizadeh et al., 2022). Research on air quality (i.e. indoor environment) and ventilation in school learning spaces is common worldwide (Andamon et al., 2019). The popularity of this area of research is driven by two primary factors: firstly, school learning spaces accommodate a high number of children exposed to pollutants from diverse indoor and outdoor sources over extended periods (Chithra & Nagendra, 2018). Secondly, school premises often undergo less frequent inspections concerning maintainability and eco-friendliness, contributing to a regular occurrence of reported poor IAQ in schools globally (Ruggieri et al., 2019). Children are vulnerable to poor IAQ due to their underdeveloped immune systems, respiratory tracts, and body mass indexes, necessitating a higher air intake within enclosed spaces (Chithra & Nagendra, 2018; Yassin & Pillai, 2019). According to Andamon et al. (2019), students spend up to 90% of their developmental years indoors at school, accumulating roughly 13,000 hours throughout their academic journey from preschool to Standard 12. Given the extensive time students spend indoors, the presence of indoor air pollutants within school premises potentially compromises a healthy indoor environment, impacting the physical and mental health of children (Bennett et al., 2019; Yassin & Pillai, 2019). The presence of pollutants within school premises and their impact on the internal environment are influenced by three significant factors: temperature fluctuations, low humidity, and aeration rates (Reche et al., 2014). These factors affect Indoor Environment Quality (IEQ), leading to health concerns and thermal discomfort within the school premises (Torresin et al., 2018).

Research has documented extensive reports on the health concerns of poor indoor conditions in classrooms. For instance, Bluyssen (Bluyssen, 2017) noted that unhealthy indoor conditions, marked by pollutants, have been linked to increased student absenteeism, directly affecting their academic performance. Roy (Roy, 2022) observed that prolonged exposure to contaminants in school premises has been linked with a heightened likelihood of developing severe health issues, like respiratory, pulmonary, and cardiovascular illnesses. Andamon et al., (Andamon et al., 2019) showed a direct association of poor ventilation rates within school premises with lower academic performance, emphasising the need to address these issues and create a learning environment that prioritises both students' cognitive and physical health development.

Likewise, previous studies have quantified the direct correlation between aeration rates and the percentage of aerial disease spread (Andrade et al., 2018; Sun & Zhai, 2020) in indoor spaces. For example, Wang and Hong (Wang & Hong, 2023) emphasises that lower ventilation rates in confined spaces contribute to transmitting airborne diseases like tuberculosis and SARS. Wei et al., (Wei et al., 2023) notes that elevated risk of airborne disease transmission is pronounced in higher-occupancy spaces, making school classrooms susceptible to hotspots. According to Dai & Zhao (Dai & Zhao, 2020), in order to keep transmission rates below 1% in confined spaces, a consistent aeration rate of 7 Air Changes per Hour (ACH) should be maintained for 2 hours of continuous teaching in classrooms.

Likewise, in New Zealand, poor IAQ classroom standards have been associated with severe health issues in children, including respiratory infections (Taptiklis & Phipps, 2017). Various factors contribute to poor IAQ conditions in school classrooms, such as lower ventilation rates causing stale environments, outdated designs, and the age of classrooms without prioritising IAQ (Papadopoulos et al., 2023). These are exasperated by higher classroom occupancy rates, which lead to elevated carbon dioxide concentrations, and the accumulation of indoor pollutants further impacts health and learning outcomes.

Addressing poor IAQ conditions in school classrooms requires a holistic approach, necessitating stakeholder collaboration to create conducive classrooms that foster health and academic performance (Zivelonghi & Giuseppi, 2024). But then, inappropriate IAQ standards and the impracticality of achieving stipulated standards have led to consistently unhealthy learning environments. Compounded by the recent challenges posed by the COVID-19 pandemic, there is a likely chance that these IAQ classroom standards are insufficient in providing a conducive learning environment for school children. For instance, a critical review of existing school design guidelines in New Zealand by Crooks et al. (Crooks et al., 2022) suggests that maintaining optimal (IAQ) within school rooms may need to be fully addressed, constituting a gap that needs to be filled to ensure safer learning environments.

According to Sutherland et al., (Sutherland et al., 2022), strategic steps must be taken to bridge the above gap to minimise exposure to IAQ pollutants, enhance ventilation rates, and improve IAQ standards. Our study aimed to bridge this gap and ascertain the robustness of the New Zealand DQLS (2.0) IAQ standards in enhancing the resilience of school facilities with measures that prioritise the health and well-being of all users. In this paper, we compared the New Zealand DQLS (2.0) IAQ standards with the IAQ standards of the OECD countries.

Differences among the standards are identified, and improvement opportunities are highlighted for the NZ DQLS (2.0) IAQ standards.

4.2 Background

4.2.1 IAQ in schools (OECD Countries)

The scientific community has increasingly focused its research on indoor air quality (IAQ) within school classrooms (Zemitis et al., 2023). The Global Burden of Disease Risk (GBDR) assessment has highlighted the significance of IAQ by ranking it 9th among health-related concerns. This recognition underscores the importance of addressing IAQ issues in educational settings to safeguard the health and well-being of students and educators (Hu & Cheng, 2022). The findings from the GBDR assessment shed light on the urgent need for effective measures and interventions to improve IAQ in schools (Forouzanfar et al., 2016).

Children across the globe spend a significant amount of time in classrooms as mandatory instruction hours for primary and secondary education. Figure 4.1 shows the compulsory average instruction hours between 2015 and 2021 in OECD countries. As shown in Figure 4.1, children in developing countries typically spend 10 to 15 per cent of their first 18 years of school life in educational premises, primarily within the confines of a classroom (OECD, 2015, 2016, 2017, 2018, 2019, 2021). The X-axis in Figure 4.1 shows the OECD year from 2015 to 2021, and the Y-axis shows the annual hours.

Classrooms often struggle to maintain healthy indoor air quality. Extensive research conducted in developing countries has consistently demonstrated the significant health implications of poor IAQ (Saffell & Nehr, 2023). A compelling body of research underscores the critical need for strategic actions and improvements to safeguard the health and well-being of students in these environments (Diaz et al., 2021; Ding et al., 2022; Korsavi et al., 2020; Stabile et al., 2016; Temprano et al., 2020).

Achieving good IAQ in conventional classroom designs is often strenuous. Due to their complex designs, conventional classrooms have less indoor mobile space and less availability to adapt or adjust to the surrounding environment (Haddad et al., 2017). To maintain healthy IAQ within the classroom, the teaching staff completes most of the adaptive measures, like opening windows and doors, either at the children's request or because of their discomfort (Zhang & Bluyssen, 2021).

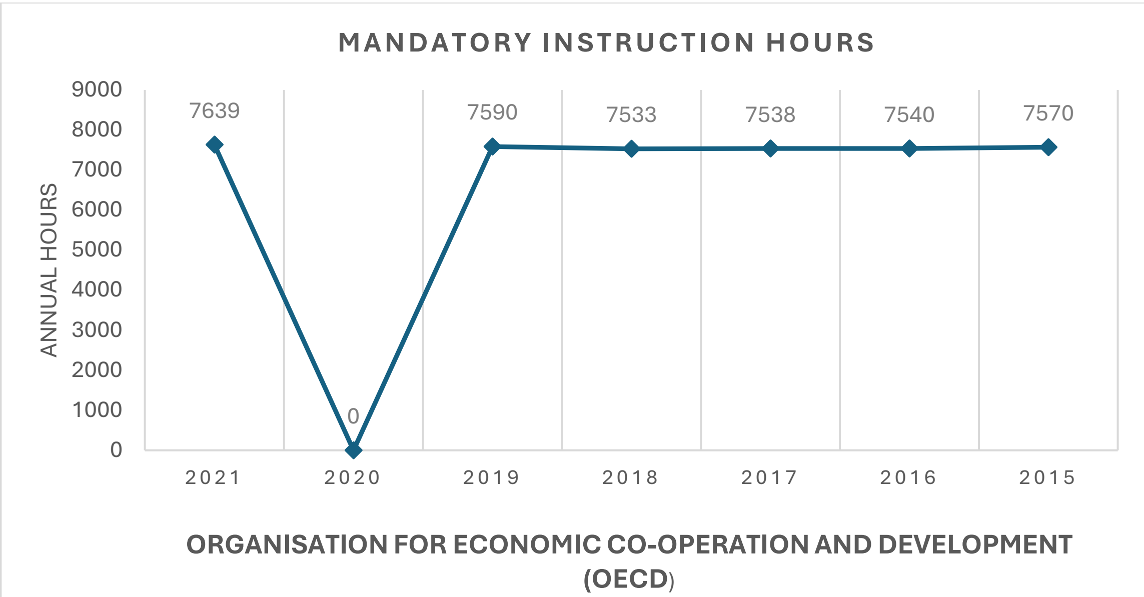

Figure 4.1: Mandatory Instructing Hours per year OECD (2015 – 2021)

Achieving good IAQ in conventional classroom designs is often strenuous. Due to their complex designs, conventional classrooms have less indoor mobile space and less availability to adapt or adjust to the surrounding environment (Haddad et al., 2017). To maintain healthy IAQ within the classroom, the teaching staff completes most of the adaptive measures, like

opening windows and doors, either at the children's request or because of their discomfort (Zhang & Bluyssen, 2021).

The impact of pollutants is dependent on indoor and outdoor air quality. Some of the pollutants which make IAQ worse are human generated; for instance, the odourless gas, carbon dioxide, and pollutants emanating from materials used in the building (Mohammadi & Calautit, 2022). In addition, pollutants coming from cleaning materials and resources used in performing educational tasks affect the indoor environment (Lucialli et al., 2020). Pollutants generated from the outside environment result from outdoor activities, weather conditions, location, and proximity of school classrooms to roads (Becerra et al., 2020). Another factor that seriously impacts the IAQ includes window operating actions, as in naturally ventilated classrooms, it plays a vital role compared to mechanically ventilated classrooms (Diaz et al., 2021).

4.2.2 Factors Impacting IAQ in School Classrooms

In a comprehensive study conducted by (Korsavi et al., 2020), the factors impacting IAQ in dwellings were examined through the lens of three main categories: context, occupant, and building. Two distinct levels were identified within the context category: macro and micro. The macro level encompassed climatic and outdoor conditions such as weather patterns or seasonal variations, while the micro level focused on factors like outdoor temperature and airflow through windows (Settimo et al., 2023). Occupant-related aspects were found to play a crucial role and included behavioural actions, the number of occupants, specific tasks performed within the dwelling, the age and nutritional habits of occupants, maintenance and operational practices, the duration of time spent indoors, and the individual comfort levels of occupants (Ebuy et al., 2023). The building-related aspects identified in the study included the location of the premises, the number of windows and doors present, the design of the building envelope, ventilation rates and system type, the total volume of the area, carbon dioxide levels resulting from exhalation, and the level of air tightness (Cakyova et al., 2021).

This comprehensive categorisation provides a framework for understanding the various factors contributing to IAQ in dwellings. Policymakers and researchers can develop targeted strategies to improve indoor air quality and promote healthier living environments by considering the context, occupant, and building-related aspects (Quesada-Molina & Astudillo-Cordero, 2023). As shown in Figure 4.2 below, occupant-related elements can significantly impact indoor air quality. Children's bodies are less mature than adults, making them more susceptible to environmental hazards. Due to smaller body organs, their immune system is not fully developed.

Moreover, their respiratory tract is in a developmental stage, so their breathing rate is higher in comparison to adults (Bayramova, 2023). In addition, the heat released from children's bodies is approximately 85% more than that released from adults due to their higher metabolism rates. The metabolism process in the human body is associated with the generation of carbon dioxide, which ranges between 3.3 cm3/s to 5.8 cm3/s for children, depending upon the activities they are engaged in (Korsavi et al., 2020).

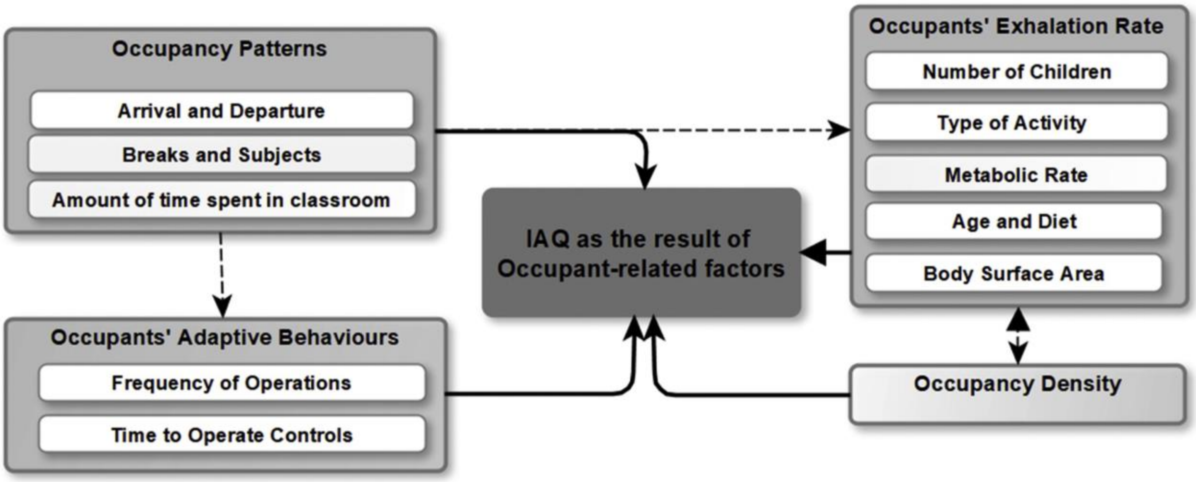

Figure 4.2: Occupant–related factors impacting IAQ

Source: (Korsavi et al., 2020)

4.2.3 Indoor Air Quality Parameters

Beings spend a significant portion of their life indoors approximately (around 90 percent), and children predominantly stay in classrooms, making school premises like second homes (Ackley, 2017). This high indoor exposure emphasises the significance of IAQ, especially in places like schoolrooms where maintaining substantial distance can be challenging. The pandemic has intensified the focus on classrooms as potential sources of COVID-19 transmission, primarily through airborne means (Guo et al., 2023).

In order to balance costs and maintain both standard thermal comfort and healthy IAQ, natural aeration is recommended as the optimal solution. Natural ventilation effectively reduces the transmission of airborne pathogens (Bhagat et al., 2020; Melgar et al., 2021). However, managing thermal conditions in colder months, crucially dependent on natural ventilation, adds complexity to spaces like classrooms. The (Control & Prevention, 2021) suggests circulating more cycles of fresh air to achieve healthy indoor air quality, especially during colder weather.

4.2.4 Carbon dioxide and ventilation

Carbon dioxide is a natural gas that's harmless in lower concentrations. Monitoring its levels in parts per million (ppm) is a way to check indoor ventilation. CO2 concentrations vary throughout the day. Higher ppm can indicate poor ventilation (Cavallini Rodriguez et al., 2022). However, low CO_2 levels are a positive indicator, but they don't guarantee a clean atmosphere. Other airborne contaminants, like pathogens, might still be present. Ventilation is crucial for designing and operating schools. It involves naturally or mechanically replacing contaminated air with clean air (Raymenants et al., 2022). Ventilation rates are measured in Litres per second per person or per square meter. The choice of ventilation method depends on the building type, usage, and activities (Ahmed et al., 2023).

Spacing management and design are vital in efficient ventilation, especially in densely populated buildings. Natural and mechanical ventilation methods are standard, but natural ventilation is recommended for indoor air quality (IAQ) (Müller et al., 2023). Studies during and post-COVID-19 emphasise natural ventilation's effectiveness in maintaining good IAQ and minimising contagion risk. The World Health Organization, (2021a) recommends natural ventilation, especially during winter, when inadequate ventilation is standard in schools (Buonomano et al., 2023).

4.2.5 New Zealand Classrooms and Indoor Air Quality (IAQ)

The New Zealand Building Code recommends incorporating natural ventilation in buildings by requiring a minimum net openable area for windows and other openings to be equivalent to at least 5% of the floor space (Ackley et al., 2022). Learning spaces achieving air changes per hour (ACH) rates above five to six ACH have CO2 concentrations below 800 ppm, indicating adequate ventilation. Recent collaborative studies in New Zealand classrooms show that a 5 cm window opening, around 50% of the window, with a 10% net ground area ratio, can quickly achieve ventilation rates of 5 ACH (Ackley et al., 2022). Partially open windows and additional support like fans can readily achieve adequate ventilation rates. But then, achieving adequate ventilation rates in naturally ventilated classrooms requires behavioural adaptability. Understanding factors that support or hinder adequate ventilation is crucial. Figure 4.3 illustrates the recommended CO_2 concentration and ventilation standards in New Zealand schools and classrooms (Ackley et al., 2022).

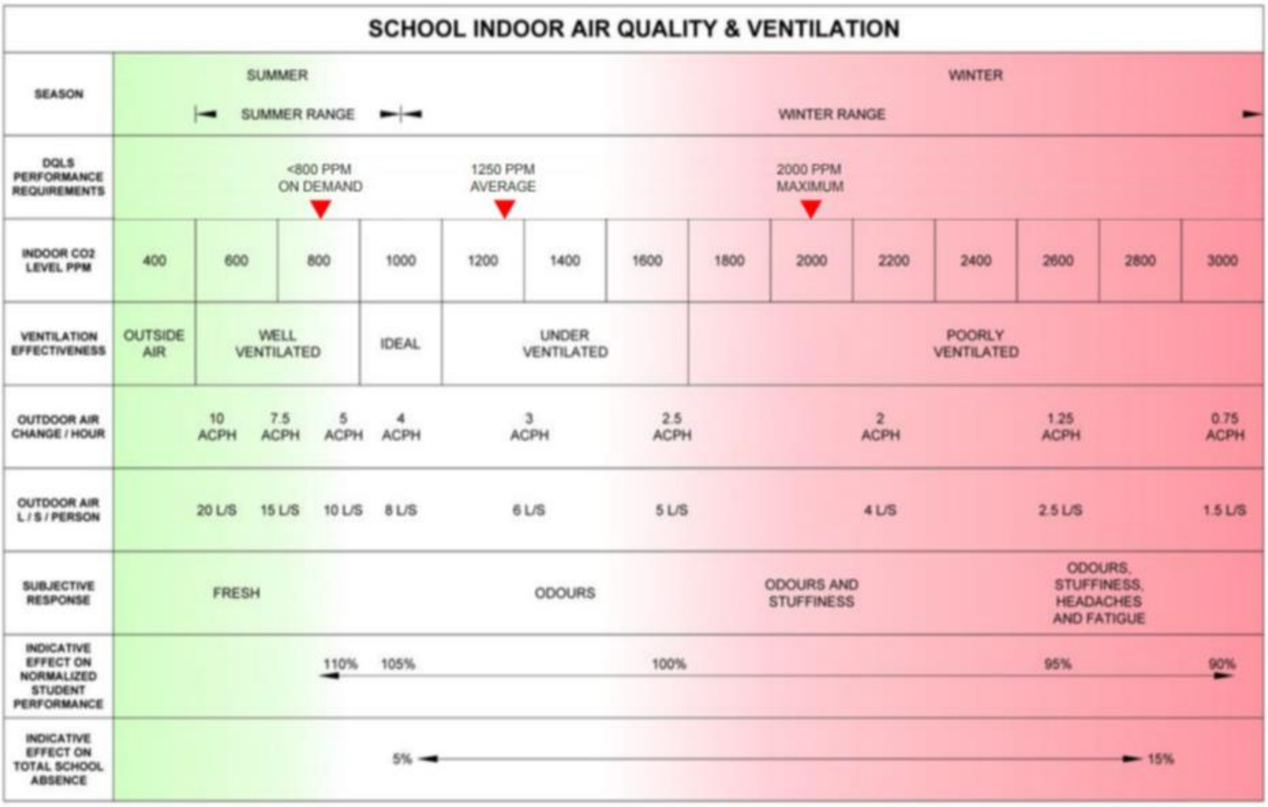

Figure 4.3: Recommended standards for CO_2 concentration and ventilation

Source: (Ministry of Education, 2022)

4.2.6 Impact of Carbon Dioxide and Ventilation in the School Classroom

A substantial body of research has investigated the link between carbon dioxide (CO_2) concentrations and potential health impacts, focusing on respiratory and cardiovascular problems (Du et al., 2020; Mishra et al., 2020; Wargocki et al., 2020). Studies focusing on children's performance and cognitive abilities suggest a noteworthy correlation with exposure to carbon dioxide levels. Chatzidiakou et al. (2015) proposes that monitoring carbon dioxide serves as a useful proxy for assessing Indoor Air Quality (IAQ), indicating lower indoor pollutants and toxic particle elimination. However, a study challenges the concept that carbon dioxide exposure solely causes declines in children's cognitive performance, highlighting the multifaceted nature of IAQ effects (Mishra et al., 2020).

While elevated carbon dioxide levels in classrooms may signal ventilation issues, it's crucial to recognise other factors influencing the indoor environment and cognitive abilities. Indoor pollutants, allergens, temperature, relative humidity, illuminance, and individual factors like sleep cycles, health, and nutrition collectively contribute to performance (Mewomo et al., 2023). This complexity underscores the need for a comprehensive investigation beyond carbon dioxide levels to understand the intricate relationship between IAQ and cognitive performance (Wargocki et al., 2020)

The global facts on the adverse physical conditions and implications of prolonged connection to poor IAQ are expanding rapidly, particularly impacting the respiratory and cardiovascular systems (Franklin et al., 2019). Respiratory illnesses, exacerbated by factors like air pollution, poor IAQ in homes and schools, and changing weather patterns, are predominant in Western countries. Associations between unhealthy IAQ and asthma development have been established, with ongoing research exploring cardiovascular implications (MacIntyre et al., 2014; Uzoigwe et al., 2013).

Moreover, the primary cause of poor IAQ is often linked to higher carbon dioxide concentrations (Rodero & Krawczyk, 2019). Although poor ventilation rates may not directly impact health, they contribute to environmental conditions, potentially leading to sick building syndrome. Inadequate ventilation can facilitate the spread of infections within indoor environments, emphasizing the significance of optimal ventilation rates in schools for healthy IAQ (Sun et al., 2011). Ventilation is crucial in controlling contaminants, maintaining comfort, and removing classroom odours. Studies indicate that increased ventilation rates lead to improved attendance and health among school children, demonstrating a positive correlation between IAQ and academic outcomes (de Gennaro et al., 2014; Haverinen-Shaughnessy et al., 2011; Mendell et al., 2013; Wargocki & Wyon, 2013).

New findings directly link carbon dioxide concentration, ventilation rates, IAQ, and children's academic outcomes. Lowering carbon dioxide levels resulted in a substantial improvement in children's performance and accuracy. A decrease from 2000 to 900 ppm led to a 12% and 2% enhancement in performance and accuracy, respectively. Improved attendance was also noted, reinforcing the connection between IAQ improvements and overall health and productivity in educational settings (Wargocki et al., 2020). Adequate ventilation is critical in cultivating a healthy indoor environment, potentially reducing harmful contaminants, and enhancing overall well-being.

Maintaining proper ventilation rates of 5-6 (ACH) is crucial, and partially active windows and doors can support achieving these rates (Health and Safety Executive, 2022). Clerestory openings offer relief by reducing draught effects, and a combination of purging and heating in the cycle ensures good air quality and comfortable thermal conditions. The WHO (2021a) recommends 10 litres per second per person (l/s/p) of outdoor air for healthy indoor air quality. This is supported by the (101, 2018), emphasising the importance of maximising classroom airflow rates through window and door openings. Refer to Table 4.1 for standards on indoor air quality and thermal comfort in school classrooms in Western countries.

4.2.7 Thermal Comfort

Assessing the indoor environment's thermal comfort is often called independent evaluation, as it considers individual satisfaction. However, children and adults differ in their assessment due to children's vulnerability to higher temperatures, influenced by their higher metabolism rates and multitasking during school hours (Cheng & Brown, 2020; de Dear et al., 2015). The adaptable thermally comfortable range for individuals is influenced by exposure to outdoor conditions. Occupants spending more time in buildings relying on natural ventilation are less vulnerable than those in mechanical ones, with a broader thermally comfortable range. It's crucial to note that an individual's comfort range varies based on factors like outdoor temperature, airflow, humidity activity level, and clothing (Lau et al., 2019; Yao et al., 2010). The key variables determining thermal comfort include air temperature, mean radiant temperature, relative humidity, and air velocity. Relative humidity (RH) and temperature are interconnected, with temperature variations often causing RH fluctuations. However, within the 40 to 70% RH range, occupants are generally not highly sensitive to humidity changes (Thomas, 2006). While humidity variations do not directly impact thermal comfort, their influence becomes more pronounced at higher temperatures and metabolic rates (Jin et al., 2017; Jing et al., 2013).

4.2.8 Impact of Thermal Comfort in a School Classroom

Thermal comfort is a crucial aspect of Indoor Environmental Quality (IEQ), influencing occupants' physical and mental conditions, and is subject to individual thermal behaviours and cultural expectations (Nicol & Stevenson, 2013). Described by (Hensen, 1991) as "a state in which there are no driving impulses to correct the environment by behaviours," thermal comfort is more of a mental state than a fixed condition. ASHRAE 55 defines it as "the condition of the mind in which satisfaction is expressed with the thermal environment" (ASHRAE, 2021). Al-Absi et al. (2022) identified six primary factors affecting thermal sensation depicted in Figure 4.4 below:

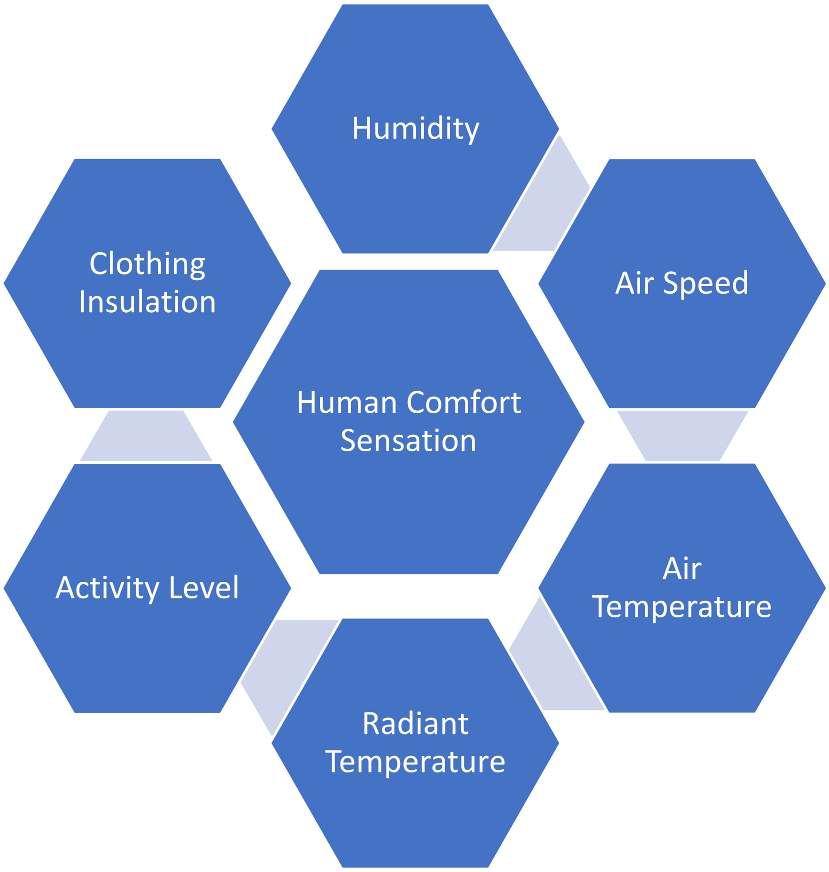

Figure 4.4: Primary factors affecting thermal sensation

The comfort within a classroom is vital for students' productivity and well-being (Ackley, 2021). Various studies have established a correlation between improved academic performance and children's thermal comfort, emphasising the impact of even slight temperature changes on learning abilities. Maintaining optimal conditions, particularly in the temperature range of 20 to 25℃, positively influences learning outcomes.

Temperature and Carbon dioxide levels and adequate ventilation can effectively maintain occupants' cognitive functioning and well-being. Adequate ventilation rates are quite effective in diluting the pollutants and maintaining acceptable ranges for carbon dioxide concentrations. The total number of occupants in the classroom and their activity level significantly influence the concentration of carbon dioxide and heat gains, which further require necessary adjustment with ventilation strategies. The size of the classroom can positively influence the effectiveness of ventilation rates.

4.3 Methodology

This study aimed to establish the robustness of the prevalent IAQ standard for CO2 and temperature levels in the NZ DQLS document. To achieve the aim of this study, we compared the NZ DQLS's IAQ standard with standards from the Organisation for Economic Co-operation and Development (OECD) countries. This ensures that the comparison is carried out between similar economic and climatic countries selected for comparison.

Firstly, we selected the IAQ standards in the following OECD countries: the United States of America, the United Kingdom, European Union Countries, and Canada. These standards include ASHRAE 62.1, CIBSE, WHO Air Quality Guideline(AQGs), EN-15251, Building Bulletin 99 and Building Bulletin 101. These IAQ standards were compared with the current NZ DQLS document's IAQ standard (version 2.0, 2022) (Ministry of Education, 2022) published by New Zealand's Ministry of Education (MOE) and the Building Research Association of New Zealand (BRANZ).

ASHRAE 62.1 (ASHRAE, 2019) is a recognised standard for designing ventilation systems and establishing acceptable ranges for IAQ. It provides measures for both new and older non-residential dwellings and aims to minimise the adverse health effects resulting from poor IAQ. CIBSE TM57 (CIBSE, 2015) offers valuable information related to school buildings, covering various stages from early design to completion. The document focuses on aspects such as acoustic design, lighting design, ventilation design, overheating and cooling design, heating and thermal comfort design, and energy demand. The WHO Air Quality Guidelines (AQGs) (WHO, 2021a) underscore the critical importance of addressing Indoor Air

Quality (IAQ) and Thermal comfort in the school environment. Children spend a significant portion of their time in classroom, the guidelines emphasise the need for standard to safeguard their health and wellbeing. The WHO (2021a) aims to mitigate the adverse health conditions associated with poor indoor environmental conditions by setting minimum guidelines for temperature, ventilation, and pollutants. EN-15251 (Comite'Europe'en de Normalisation, 2007) establishes measurable parameters for indoor environmental quality in commercial dwellings, specifically addressing the designing and evaluation of energy efficiency, quality of indoor air, comfort performance, lighting, and sound levels. The document provides a clear understanding of non-statutory standards for educational learning spaces. It presents minimum space requirements for school classrooms, ensuring adequate areas for occupants to maintain a healthy IAQ. The standard for comparison includes temperature range, carbon dioxide concentration, ventilation rates, classroom size, occupancy, and occupant density. This study's results and discussion section presents the findings from these reports. Building Bulletin 99 by (DfES, 2006) is a comprehensive document developed by department for education in the United Kingdom. It provides guidance and standard for creating safe, healthy, and conducive learning environment in school. Building Bulletin 99, aims to meet high standards for school indoor environments focusing on well-beings, comfort, and academic achievement of students. The document provides technical guidance on IAQ standards and Thermal comfort criteria with respect to design, number of occupancy, space planning, ventilation, and performance. Building Bulletin 101 is a guidance tool published by the Department for Education in 2006 in the United Kingdom. BB101 version 1, which was recently updated in 2018. The BB101 version 1 tool sets out the regulations, standards, and guidelines on school ventilation, thermal comfort, and indoor air quality. The main drivers of this guidance tool include providing ventilation standards for schools. Establishing minimum ventilation rates for adequate fresh air supply to occupants. Addressing the importance of thermal comfort and guiding people to maintain comfortable room temperature. Focusing on the health and well-being of students considering air quality and temperature regulation (DfES, 2018).

The MOE-initiated DQLS provides appropriate IAQ and thermal comfort guidelines in NZ classrooms and learning spaces. The document aims to ensure optimal learning environments in newly constructed schools. Originally released in 2007 as separate documents for IAQ and thermal comfort, DQLS was updated and combined in 2017 (version 1.0). The 2022 update (version 2.0) incorporates revised standards for air quality, thermal performance, heating, and classroom ventilation. DQLS 2.0 also outlines mandatory requirements for air quality, temperature, thermal performance, and indoor environment monitoring. The DQLS 2.0 update strengthens mandatory requirements to align with the Ministry of Education's (MOE) 2030 School Property Strategy. This strategy prioritises well-being and fosters quality learning environments that support diverse teaching and learning approaches. The update reflects the evolving landscape of educational space design and commissioning, now overseen by a combination of national and regional governing bodies (Ministry of Education, 2022).

A key driver for the stricter IAQ&TC requirements is the recognition that most New Zealand primary schools (roughly 90%) rely heavily on natural ventilation through windows and doors. These requirements aim to ensure thermally comfortable learning spaces that can effectively support various teaching styles and learning activities. The emergence of COVID-19 in New Zealand (February 2020), mirroring global concerns, spurred the Ministry of Education (MOE) to update the DQLS 2.0 (2022) with a renewed emphasis on ventilation's role in mitigating airborne disease spread, including COVID-19. This revision aims to create healthier and more comfortable learning environments through Enhanced requirements for fresh air intake and distribution, Improved guidance for heating and cooling strategies tailored to regional climates, Enhanced design verification and compliance measures, including mandatory modelling for larger buildings, The incorporation of indoor environmental monitoring tools in each classroom to facilitate continuous monitoring of ventilation system performance.

The New Zealand Ministry of Education prioritises healthy classrooms through improved IAQ and thermal comfort. DQLS mandates address these aspects alongside acoustics and lighting, demanding a holistic design approach. As IEQ is a complex system of interrelated variables (IAQ, thermal, acoustics, lighting), designers must consider their combined impact during design and commissioning to ensure an optimal learning environment (Ministry of Education, 2022).

The IAQ standards were compared based on the following factors relating to IAQ and thermal comfort:

- Temperature:
- Carbon dioxide
- Ventilation rate
- Occupancy
- Occupancy density
- Classroom size

The key factors selected for this comparative study are intrinsically linked to the assessment and optimisation of IAQ and thermal comfort in a classroom environment. These factors influence indoor vital conditions and directly impact health, well-being, and performance. For instance, temperature is a critical factor affecting thermal comfort and is associated with cognitive functioning and productivity. Carbon dioxide concentrations are widely used as a proxy measure to calculate ventilation efficiency and overall IAQ. Higher

CO_2 concentrations are associated with an inadequate supply of fresh air. Moreover, ventilation rates directly influence the dilution and removal “of indoor pollutants, including excessive CO_2, and the thermal regulation of the indoor space.

The number of occupants and their ”ensi’y within the classroom is directly associated with generating carbon dioxide and indoor pollutants. Appropriate occupant density ensures sufficient air volume per person, preventing overcrowding, which can lead to poor IAQ and thermal discomfort. The classroom size plays an important role in air volume and the ability to achieve optimal ventilation, temperature distribution, and overall healthy environmental quality. Hence, all the above factors chosen for this comparative study across OECD standards help to identify best practices and highlight the areas of improvement to achieve optimal IAQ and thermal comfort in the classroom.

The findings and discussion are provided In Section 4.4 below. These are discussed based on the underlying theories supporting these standards.

4.4 Findings and Discussion

Table 4.1 below provides an overview of the IAQ standards compared with the NZ DQLS IAQ and Thermal Comfort Standard. The table shows that the NZ DQLS standards differ slightly from most OECD countries’ standards. For temperature, the NZ DQLS standards stipulate a range similar to WHO AQG, Building Bulletin 101, and EN 15251 standards. While the minimum CO_2 level is the same as CIBSE and EN 15251, the maximum CO_2 differed significantly. For ventilation rate, the NZ DQLS standard was closely aligned with the WHO AQG standard and CIBSE standards but higher than the ventilation rate specified in ASHRAE 62.1 and EN 15251. For occupancy, occupant density and room size, the standards differed significantly. While ASHRAE 62.1 and BB 99 specified the occupancy and occupant density required in particular classroom sizes, CIBSE only identified the required occupant density. EN 15251 specified the occupancy and occupant density, while NZ DQLS noted the required occupancy for a classroom size.

Table 4.1:Comparison of IAQ and Thermal comfort parameters from OECD countries

OECD International Standards	Temperature	Carbon dioxide	Ventilation rate	Occupancy	Occupant Density	size
ASHRAE 62.1 (ASHRAE, 2019)	22°C Average	1000 ppm	6.7 -7.4 L/s/p	25	4 m2	100 m2
CIBSE TM57 (CIBSE, 2015)	21°C Maximum	800 -1000ppm	10 – 15L/s/p	-	2 – 4 m2	-
NZ DQLS (Ministry of Education, 2022)	18°C - 25°C	800 – 2000ppm	5 – 10 L/s/p	30	-	~75 m2
WHO AQG (WHO, 2021a)	18°C - 24°C	1000 – 1500ppm	10 L/s/p	-	-	-
EN 15251 (Comite'Europe'en de Normalisation, 2007)	20°C - 24°C	800 -1400ppm	5 – 8 L/s/p	23	2 – 3.1 m2	-
BB 99/101 (DfES, 2018; DfES, 2006)	20°C-25°C	1500 ppm	8 -10 L/s/p	30	2.3 m2	70 m2

4.4.1 Carbon Dioxide and Ventilation Rate Standards

In post-pandemic times, natural ventilation in educational settings has gained importance for sufficient ventilation rates. Evidence shows that it ensures a clean air supply, reducing the risk of airborne contagions. Studies suggest that approximately 4 square meters of window openings are needed in classrooms for 8 to 9 litres per second per person ventilation rates in summer, and around 2 square meters are sufficient in winter with effective heating (Papadopoulos et al., 2023). An optimum average CO_2 concentration of 800–900 ppm is linked to improved health and academic performance. Concentrations close to 900 ppm or lower significantly enhance children's performance. Ventilation rates and cognitive ability studies show that increasing ventilation rates from 15 to 25 litres per second per person can improve cognitive performance by an additional 10 percent (Kuramochi et al., 2023). A concentration of 2100 ppm indicates very low ventilation rates, causing discomfort to occupants.

International standards recommend minimum ventilation rates for classrooms. Studies show that doubling ventilation rates significantly improves learning outcomes, with a more substantial improvement observed in schools compared to office buildings (Wargocki et al., 2020). Approximately 90 percent of classrooms in New Zealand rely on natural ventilation (Ackley et al., 2022; Trompetter et al., 2018). While there are no specific standards for minimum ventilation, regulations propose CO_2 concentration as a proxy. It suggests that average CO_2 should not exceed 1500 ppm during the day or exceed 3000 ppm during peak learning hours (Bennett et al., 2019). However, DQLS 2022 represents a significant improvement and a tightening of indoor carbon dioxide requirements for New Zealand School classrooms. The recommended daily average CO_2 concentration during occupied hours is set at 800 ppm. This 800 ppm is considered the ideal "Design Goal" to maintain optimal IAQ. However, the mandatory maximum daily average for CO_2 concentration during occupied hours is 1250 ppm. This 1250 ppm represents the upper limit before the IAQ is deemed inadequate and in need of improvement. Furthermore, the DQLS, 2022 specifies that the maximum permissible peak CO2 concentration must not exceed 2000 ppm at any point during the teaching period. The maximum permissible limit of 2000ppm act as an emergency limit, indicating to take immediate action to purge the indoor air and try to lower the CO2 concentration to "Design Goal" of 800 ppm. Well, the designed limit for CO2 800 to 2000ppm, in DQLS, 2022 document appears considerably reasonable to maintain healthy and comfortable IAQ.

On comparison with other OECD countries standards, ASHRAE 62.1 caps CO2 concentration at 1000 ppm, CIBSE recommends the range of 800 -1000 ppm, WHO AQS allows up to 1500 ppm, Building Bulletin 101 recommends up to 1500 ppm and the EN15251 ranges 800 – 1400 ppm. However, it is important to note that DQLS, 2022 version 2.0, also specifies a recommended daily average of 800 ppm and a mandatory average daily limit of 1250 ppm. These limit clearly states the DQLS thresholds aligns closely with OECD standard. Likewise, the peak limit of 2000 ppm in DQLS, 2022 may still be higher in comparison to other OECD countries, the overall CO2 concentrations limits appears to be concerted effort. This advancement in DQLS, 2022 to regulate CO2 concentrations, clearly signifies the New Zealand Ministry of Educations commitment to provide optimal IAQ for students, staff and co-workers to their health and productivity. The advancement reflects the positive attitude in aligning with international standards for IAQ.

The ventilation rate standards for school classrooms vary across the OECD countries. The ASHRAE 62.1 standard specifies a range of 6.7 to 7.4 Liters per second per person (l/s/p), while the CIBSE guidelines recommend a higher range of 10 to 15 l/s/p. In contrast, the New Zealand DQLS document outlines a lower ventilation rate of 5 to 10 l/s/p. The WHO Air Quality Guidelines (AQGs) align more closely with CIBSE, suggesting a rate of 10 l/s/p. The

EN-15251 standard falls in the middle, prescribing a range of 5 to 8 l/s/p. Interestingly, the Building Bulletin 101 (BB101) standard recommended a ventilation rate of 8 to 10 l/s/p, which sits between the upper and lower bounds of the other guidelines. This diversity in ventilation rate requirements reflects the different approaches and priorities adopted by each country or organization in balancing factors such as indoor air quality, energy efficiency, and practical feasibility for school design and operation.

4.4.2 Temperature Standards

The prevalent indoor temperature levels determine thermal comfort in any given space. Likewise, the indoor temperature is influenced by the outdoor temperature and fluctuates in accordance with this temperature variability. Interestingly, occupants in colder regions have been noted to be more adaptable and accommodating to exposure to colder temperatures, influencing their adaptability to colder indoor settings. As such, in classrooms where temperatures may fall below the recommended 18℃, it is likely that children would find temperatures below this threshold comfortable.

This explains why various countries have diverse thermal comfort standards (Table 4.2 below). For example, ASHRAE 62.1 suggests an average of 22℃, while the Regional Education Laboratory recommends different ranges for winter (20℃ - 24℃) and summer (23℃ - 26℃). Recommendations from the United Kingdom vary, with CIBSE suggesting a maximum of 21℃ and the National Education Union recommending a minimum of 18℃. Canada and the European Union have different ranges, with Canada suggesting 20℃ - 26℃, the EU recommending 24℃- 26℃, and the Building Bulletin 101 recommending between 20℃ - 25℃. New Zealand, with varied climates, sets a recommended range of 18℃ - 25℃ for classroom temperatures, according to the Ministry of Education. However, performance varies based on factors like design, climate, occupancy, and behaviour.

Table 4.2: International Institution Recommended Classroom Temperature Range

Source: (Sutherland et al., 2022)

Western Countries (OECD)	Institutional Recommendation	Temperature Range
United States of America	ASHRAE 62.1 (ASHRAE, 2019)	22℃ (Average)
United Kingdom	CIBSE TM57 (CIBSE, 2015)	21℃ (Maximum)
United Kingdom	National Education Union (National Education Union, 2019)	18℃ (Minimum)
United States of America	Regional Education Laboratory (REL, 2018)	20℃ - 24℃ (winter) 23℃ - 26℃ (Summer)
Canada	National Joint Council(National Joint Council, 2011)	20℃ - 26℃
New Zealand	Ministry of Education (Ministry of Education, 2022)	18℃ - 25℃
Europe	EN 15251 (Comite'Europe'en de Normalisation, 2007)	24℃ - 26℃

Achieving these temperature standards remains a complex topic. While some authors recommend using natural ventilation, which supports the sustainability crusade, others recognise the limits of natural ventilation and promote mechanical or even mixed-mode ventilation systems. For instance, NZ DQLS's IAQ and thermal comfort document emphasises the preference for natural ventilation and only recommends mechanical or mixed-mode ventilation (with cooling, where appropriate) may be considered for summertime temperature control, where natural ventilation cannot reasonably achieve the maximum temperature criteria. The mode for acceptable ventilation strategies depends upon locations based on heating and cooling degree days. Likewise, depending on the number of heating and cooling days required annually, different countries set out the climate zones that suit the ventilation system required to meet adequate IAQ and Thermal comfort conditions. Additionally, the ASHRAE 62.1 offers mechanical or mixed modes of ventilation strategy, whereas CIBSE, BB 101 and EN-15251 allow natural, mechanical, and mixed modes of ventilation depending on building type, climate zone, occupancy levels, and budget. In response to the pandemic, CIBSE issued specific guidance on ventilation to help mitigate the spread of airborne diseases like COVID-19. This guidance emphasizes increasing ventilation rates, improving air filtration, and encouraging natural ventilation where possible. The emphasis in BB99 on ensuring reliable natural ventilation through doors and windows, along with the DQLS standards, suggests a strong focus on utilizing natural ventilation whenever possible, aligning well with New Zealand's climate.

Using natural ventilation in classrooms during winter may cause discomfort due to temperature variations, known as the stack effect. That said, the performance of natural ventilation in reducing temperature levels improves in winter compared to summer due to increased airflow (Vouriot et al., 2024). In particular, cross ventilation and vertical displacement ventilation are effective against COVID-19 transmission but have limitations such as contaminant movement and heat loss. Balancing thermal comfort, energy needs, and the risk of airborne transmission is crucial when selecting ventilation modes for school classrooms (Albertin et al., 2023). Aniebietabasi (Ackley, 2021) recommends deploying combined sensors for temperature and humidity in naturally ventilated areas to understand their spatial connection better.

Most thermal comfort standards worldwide rely on two thermal comfort models to evaluate temperature levels in buildings –Fanger's model and Adaptive Model. Fanger's model recommends that the temperature range for thermal comfort is 20 ± 1 to 24 ± 2 °C, varying based on climatic conditions (Kükrer & Eskin, 2021). The newer adaptive thermal comfort model considers a broader temperature range, acknowledging the influence of individuals' interactions and adaptability with their environment.

Fanger's equations, including the Predicted Mean Vote (PMV) index, commonly assess thermal comfort in dwelling settings (ASHRAE, 2021; ISO, 2005).

$$T_{n(resi)} = 0.26 \text{ x } T_{pma(out)} + 16.75 \quad (1)$$

$$T_{lower\ 80\%\ acceptability\ limit} = 0.26 \text{ x } T_{pma(out)} + 12.25 \quad (2)$$

$$T_{upper\ 80\%\ acceptability\ limit} = 0.26 \text{ x } T_{pma(out)} + 21.25 \quad (3)$$

But then, Fanger's model has a limitation in that its PMV model doesn't encompass a wider range of thermal adaptability and dissatisfaction. As depicted in Figure 4.5, with variables such as activity levels kept constant, a minimum % dissatisfaction rate of 5% persists even when the PMV index is 0 (Hwang et al., 2009). This suggests that some individuals will remain dissatisfied with the prevalent temperature, emphasising the influence of personal preferences and perceptions of thermal comfort.

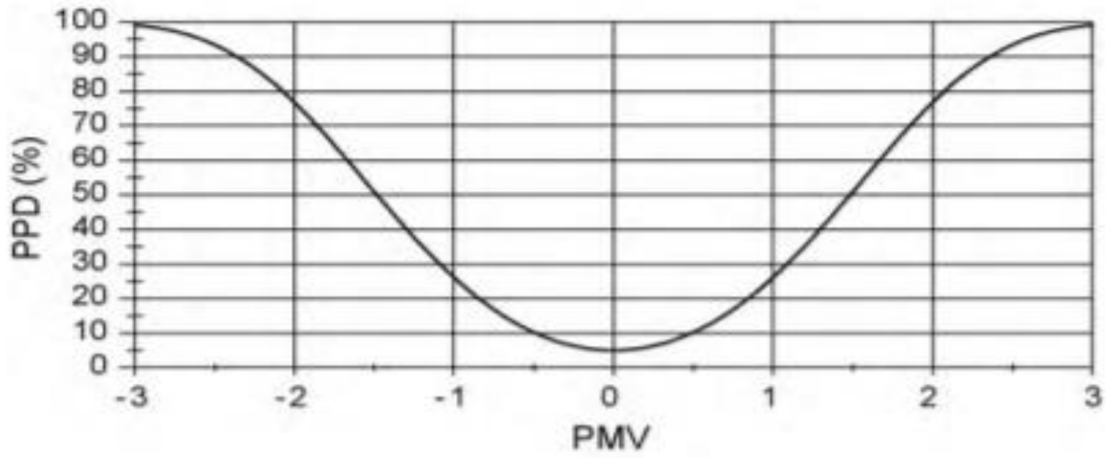

Figure 4.5: Relationship PMV versus PPD

Source: (Hwang et al., 2009)

Despite this limitation, the PMV-PPD model developed by Fanger is broadly acknowledged and utilised for assessing indoor thermal environments. It has gained prominence in mechanically ventilated buildings and is notably employed by ASHRAE 55 (ASHRAE, 2021) for evaluating thermal comfort in dwellings with mechanical ventilation heat recovery systems (MVHR) (Lin & Deng, 2008). International comfort standards like ASHRAE 55 and ISO 7730 based on Fanger's model are regarded as reliable references for evaluating thermal comfort.

ISO (2005), a global standard, employs Fanger's PMV-PPD model as the recommended method for assessing thermal comfort. According to annexure A of ISO 7730, outlines specific criteria for thermal conditions, primarily focused on sedentary activities in the winter heating period. To achieve a satisfaction rate of 80% for occupants, the specified conditions must be met (Ade & Rehm, 2020):

(1) temperature of between 20 and 24ºC

(2) air temperature difference of <3ºC (Vertical)

(3) floor surface temperature between 19 and 26ºC

(4) mean air velocity lower than 0.15m/s

(5) radiant temperature from cold surfaces of <10ºC

(6) radiant temperature from warm surfaces of <5ºC

The conditions in (Table 4.3) were predicted by ASHRAE 55 (ASHRAE, 2021)for an RH of 50%, mean air velocity < 0.15m/s, and mean radiant temperature equivalent to air temperature.

Table 4.3: ASHRAE 55 Standard recommendations for Accepted thermal comfort.

	Operational Warmth	Satisfactory Range
Cold Climatic Condition	24.5℃	23℃ to 26℃
Hot Climatic Condition	22℃	20℃ to 23℃

Source: (ASHRAE, 2021)

As illustrated in Table 4.4, the satisfactory range for thermal comfort can be categorised into three distinct zones based on PMV and PPD ranges. This framework allows for the evaluation of indoor thermal environments. Furthermore, by integrating factors like temperature, humidity, air speed, and clothing level, these comfort zones inform the design and operation of HVAC systems, ultimately promoting occupant thermal satisfaction in Table 4.4.

Table 4.4: Percentage of dissatisfied (PPD) on the basis of (PMV)

Three Comfort Zones	Predicted Percentage Dissatisfied	Scale Of PMV
1	Less than 6	-0.2 <PMV<0.2
2	Less than10	-0.5 < PMV<0.5
3	Less than15	-0.7 <PMV<0.7

Source: (ASHRAE 55, 2021)

The primary rationale behind the adaptive comfort model for dwellings relying on naturally ventilated is that human nature alteration, including psychological and physiological adjustments, can lead to broader current thermal conditions (De Dear & Brager, 2002). The Adaptive Comfort model (ASHRAE 55) is limited in application, with dwellings deemed unsuitable to all the occupants if they tend to spend more time beneath one temperature. The adaptive comfort model, pioneered by researchers such as de Dear and Brager, was not developed specifically for residential dwellings in New Zealand relying on natural ventilation. Rather, the adaptive comfort approach has been studied and applied in various commercial buildings like schools and offices. The reason is that occupants in schools and offices have greater control over their thermal adaptability via window and door operations and another adaptive mechanism (De Dear & Brager, 2002). However, it is important to note that DQLS, 2022 is not explicitly based on the adaptive comfort model. Instead, it aligns more with Fanger's Model scale of PPD and PMV indices. The distinction highlights the differences with the thermal comfort model used across OECD country's standards, with some adopting the adaptive approach and New Zealand relying more on the established Fanger-based framework.

The adaptive model mechanism (see Figure 4.6) for thermal comfort presented below is a theoretical model based on the Black Box theory, which considers several aspects: climate, culture, social, physiological, and human nature adaptations. The model is known as an adaptive predicted mean vote (aPMV) model. Research shows that the (aPMV) model, in free-running dwellings relying on natural ventilation, the predicted mean vote (PMV) is greater than the actual mean vote (AMV). This indicates that occupants with natural ventilation strategies can tolerate wider temperature ranges than those with mechanical ventilation. The aPMV comfort model might overestimate how hot students feel in naturally ventilated classrooms, common in New Zealand (cold and temperate climate). This could lead to classrooms being designed cooler than necessary, wasting energy and potentially making students uncomfortable (Özbey et al., 2022). Primary school classrooms in cold and temperate climates, relying on natural ventilation, often experience high-temperature fluctuations due to high occupancy, lower ventilation rates, and excess heat entering through windows designed for daylight (Wargocki & Wyon, 2007).

Factors such as comfort temperature, dwelling typology, solar gains, incidental gains, ventilation level and occupants can add to overheating in dwellings, which can change the thermal comfort standards (Comite'Europe'en de Normalisation, 2007).

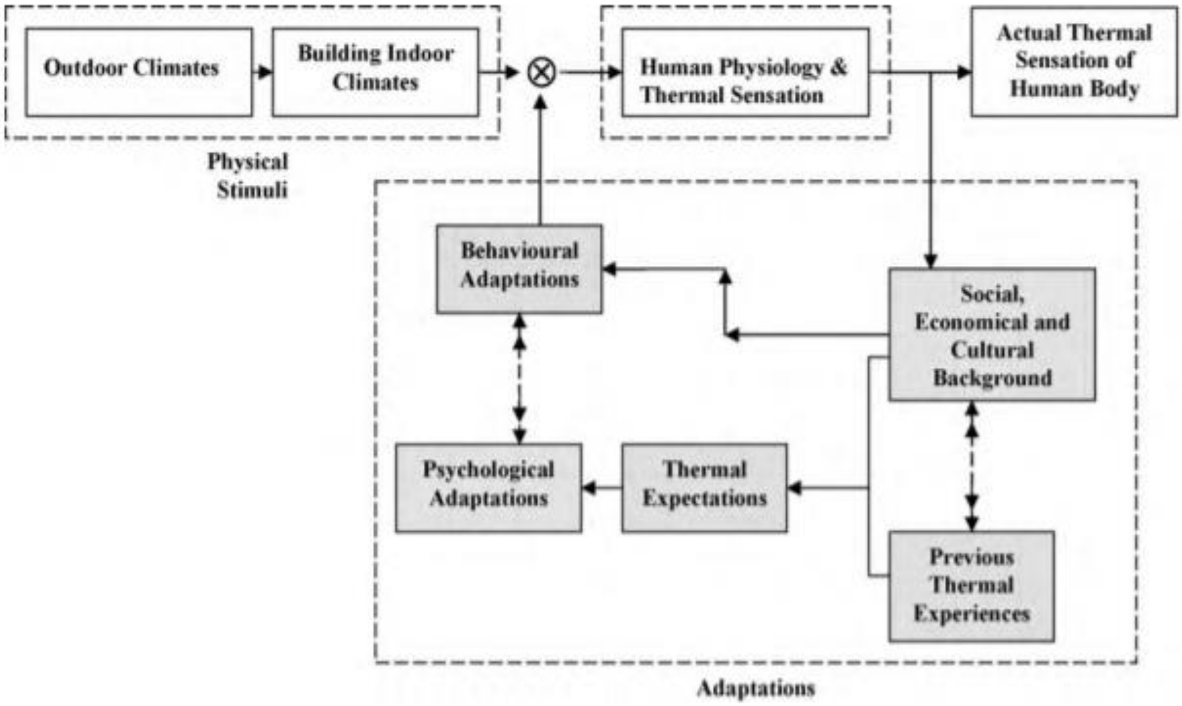

Figure 4.6: Adaptive model mechanism for thermal comfort.

Source: (Yao et al., 2010)

4.4.3 Occupancy, occupant density and room size standard

Ensuring a healthy and productive learning environment for children in school classrooms necessitates focusing on multiple aspects, including indoor air quality and thermal comfort. These factors are significantly influenced by classroom design and layout features, particularly when considering occupancy (number of students), occupant density (space per student), and classroom size. This section delves into a comparative analysis of these parameters, which strictly influence the IAQ and thermal comfort in indoor environments across OECD countries.

The recommended number of students within a classroom or occupancy varies across OECD countries' standards. ASHRAE 62.1 recommends a maximum occupancy of 25 students with a corresponding density of 4 m2 per person to a 100 m2 classroom. This approach ensures ample personal space and potentially better air quality by reducing CO2 concentration through increased air volume per person. However, it may not be possible for all schools due to space constraints and cannot be applied to universal guidelines. CIBSE TM 57, on the other hand, adopts a flexible approach by not specifying the occupancy and size of the classrooms, but it does recommend an occupant density of 2 to 4 m2. This allows room for future adjustments based on the actual classroom size to obtain desired learning outcomes, as without clear guidelines, it might not be easy to achieve optimal IAQ.

Whereas in New Zealand classrooms, the occupancy is slightly higher, with 30 in a 75 m2 classroom, implying an occupant density of around 2.5 m2/p. This recommendation balances providing sufficient space for student activities while maintaining a reasonable classroom size. While it might achieve acceptable IAQ in some cases, the findings by (Chatzidiakou et al., 2012; Katafygiotou & Serghides, 2014) state carbon dioxide in classrooms in comparison to office buildings is approximately four times. Hence, it becomes potentially significant to additional ventilation strategies, particularly when occupancy density is at the recommended limit (Korsavi et al., 2020).

EN -15251 suggests a lower occupancy of 23 students with a 2 to 3.1 m2/p occupant density. This approach prioritizes providing enough space per student, potentially achieving better IAQ and minimizing carbon dioxide concentrations. Finding from multiple studies states lower the occupant's density in classroom, is directly associated with higher carbon dioxide concentrations (Mydlarz et al., 2013; Ramalho et al., 2013; Stabile et al., 2016; Wargocki & Wyon, 2013). According to Organization and Eurostat (2017), maintaining carbon dioxide concentration within 1000 - 1500 ppm, recommends maintaining a balance of 2 to 3.1 m2/p occupant density with a maximum of 22 students. According to Building Bulletin, 99 recommends an occupancy of 30 students within 70 m2 of classroom size, which aligns with the density of occupants similar to New Zealand, 2.3 m2/p, but differs in occupancy and classroom size. Mydlarz et al. (2013) state that the minimum occupant density of 2.3 m2/p with no additional strategies (adequate ventilation rates), can significantly lead to higher carbon dioxide concentrations. Hence, maintaining adequate ventilation and healthy IAQ in such complex environments becomes challenging for designers and architects. To counter the issue of occupant density, it is said that the height of the classroom should be increased to 3.3 meters, as it can maintain significantly better IAQ (Montazami et al., 2015).

An overpopulated classroom can result in high CO_2 , higher body heat, and odor-creating less productive space, with discomfort and a stressful environment impacting performance. Korsavi et al. (2020) also state classrooms with a 2.3 m2/p occupant density will require more fresh air circulation to maintain optimal environmental conditions for children. The slight differences in classroom sizes, occupancy, and occupant density other than ASHRAE 62.1 standards, across OECD countries' standards could be due to factors like educational practices, student-teacher ratios, and cultural and space utilization in different countries. Moreover, bigger classrooms offer flexibility with layouts and space management and provide an overall learning environment, keeping health and productivity equal. In addition, mechanical or HVAC ventilation may not be a feasible option in the context of cost measurement and maintenance. Still, classrooms relying on natural ventilation can be a viable strategy to balance IAQ conditions. Notably, the New Zealand classrooms offer an occupant density of 2.3 m2/p (based on a 75 m2 classroom and 30 students). The slight difference in occupant density in comparison to CIBSE and EN – 15251 states that the New Zealand standard is not far below. However, there is still room for future research as ASHRAE 62.1 offers 4 m2 of occupant density.

The commonalities and differences show the need for a holistic approach to designing and regulating school learning environments. Continuous improvement of IAQ and thermal comfort in the classroom carefully requires considering all classroom sizes, occupancy, and occupant density together.

4.5 Conclusion

This study extensively reviews existing indoor air quality (IAQ) and thermal comfort guidelines, focusing on international standards and OECD countries. Despite ongoing research on IAQ and thermal comfort in educational learning spaces globally, many studies briefly address the health and performance impacts of poor indoor air quality. The result and discussion section critically compares IAQ and thermal comfort standards, revealing significant variations among international standards adopted by OECD countries. Factors influencing these differences include climate, occupancy, building design, spatial considerations, and local environmental exposures.

The study employs standards such as ASHRAE 62.1, CIBSE, WHO, EN-15251, Building Bulletin 99, and DQLS, concluding its three-part review: thermal comfort, carbon dioxide with ventilation, and classroom attributes. New Zealand's standards are found lacking in addressing pandemic situations, indicating a need for improvement through scientific research. In order to bridge this gap, strategic steps must be taken to enhance IAQ standards, minimize exposure to pollutants, and improve ventilation rates. In the thermal comfort comparison, the study examines the permissible indoor temperature ranges across international standards. New Zealand's more comprehensive range aligns with WHO and Canada's National Joint Council standards, while ASHRAE 62.1, CIBSE, and the UK's National Union of Education specify narrower limits. The study highlights the importance of considering occupant behaviours and providing training, knowledge, and guidance to enhance thermal comfort.

The comparison of carbon dioxide and ventilation rates delves into recommended concentrations and rates for healthy IAQ. New Zealand standards align with CIBSE (2021) and WHO, recommending a minimum of 10 l/s/p. However, ASHRAE's mechanical ventilation focus suggests a lower range. The study emphasises the significance of ventilation in reducing airborne pathogens and improving indoor air quality. Examining classroom attributes, the study underscores the impact of occupant density on carbon dioxide levels. International standards recommend a minimum occupant density of 2.3 m2/p. The study suggests reducing occupants or increasing ceiling height to meet IAQ standards. It calls for improvements in New Zealand's DQLS document regarding carbon dioxide concentration. Therefore, this study advocates for holistic optimisation of standards and guidelines, emphasising health, well-being, and performance. It identifies areas for improvement in current guidelines, particularly in addressing pandemic situations and aligning standards with health-oriented objectives. Future research should focus on a more flexible and versatile approach to indoor air quality, considering both classroom design and occupancy levels.

Chapter 5 Prologue

Having established that New Zealand's DQLS Version 2.0 standards differ from international benchmarks in Chapter 4, this chapter moves from comparative analysis to performance evaluation, asking: how do New Zealand's primary school classrooms actually perform against these standards, and what design modifications could optimise indoor air quality and thermal comfort across the country's diverse climate zones and how will it represent for Post – Covid era?

This chapter presents comprehensive building performance assessments of two prevalent primary school classroom typologies representing New Zealand's educational building stock: the Avalon block and the Canterbury block. These typologies, found in schools nationwide, were selected because they represent different architectural approaches yet share common challenges: reliance on natural ventilation, varying window configurations, and exposure to New Zealand's six distinct climate zones, from subtropical Auckland to temperate Queenstown. Using advanced parametric modelling through Rhino 7 software with Ladybug and Honeybee plugins, the research simulates classroom performance against both DQLS Version 2.0 and international standards (ASHRAE 62.1, CIBSE, EN-15251, Building Bulletins 99 and 101) across multiple criteria: adaptive thermal comfort percentages, energy loads (heating, cooling, infiltration), carbon dioxide concentrations, ventilation rates, and daylighting metrics.

This chapter comprises of three main components. First, a detailed methodology explaining the simulation approach, software selection rationale, and the specific parameters modelled including classroom geometry, occupancy profiles, thermal envelope specifications, and climate data for each zone. Second, comprehensive results presenting performance data across all assessment criteria, revealing where current standards succeed and where significant gaps exist, particularly concerning carbon dioxide management and thermal comfort in extreme climate zones. Third, the development and testing of optimal design modifications: increasing ceiling heights by approximately one meter, adjusting window placement vertically by ~0.3 meters, reducing window-to-wall ratios to 25%, enhancing insulation values for southern regions, and refining ventilation control strategies each modification tested for its impact across multiple performance dimensions simultaneously. This chapter bridges the gap between policy documents and physical reality, transforming abstract standards into measurable outcomes within actual classroom environments. The findings reveal not only current performance limitations but also demonstrate that strategic, evidence-based design interventions can significantly improve multiple aspects of classroom environmental quality simultaneously typically achieving 3-12% improvements in thermal comfort, 10-20% reductions in energy loads, and 20-30% improvements in carbon dioxide management. These quantified results provide the technical foundation for the validation work in Chapter 6 and the final recommendations in Chapter 7, ensuring that proposed guidelines rest on rigorous performance data rather than theoretical assumptions.

5. Simulation

“A Simulation-Based Study of Two Classroom Typologies: IAQ and Thermal Comfort Performance Across New Zealand’s Six Climate Zones". This chapter comprises two journal articles that have been submitted to different journals and have been accepted for publication. The details for both submitted journal articles are depicted below:

This article is published by Arya, V. K., Rasheed, E. O., & Samarasinghe, D. A. S. (2025). A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New Zealand’s Six Climate Zones: The Avalon Typology. Buildings, 15(12), 1992. https://doi.org/10.3390/buildings15121992

This article is submitted to “*Smart and Sustainable Built Environment*” from “*Emerald Publishing*” by *Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S. (2025). “A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New Zealand’s Six Climate Zones (2): The Canterbury Typology” (Accepted-SASBE-04-2025-0168)*

Abstract

Indoor environmental quality profoundly impacts student learning outcomes and teacher effectiveness, particularly in primary education, where children spend most of their developmental years. The study evaluates the primary school classrooms, comparing the Ministry of Education's Designing Quality Learning Spaces (DQLS) version 2.0 with international standards set by OECD countries to develop IAQ and thermal comfort best practices in New Zealand across six climate zones. The research evaluates indoor air quality (IAQ) and thermal comfort factors affecting students' and teachers' health and performance. Using Ladybug and Honeybee plugin tools in Grasshopper with Energy Plus, integrated into Rhino 7 software, the study employed advanced building optimisation methods, using multi-criteria optimisation and parametric modelling. This approach enabled a comprehensive analysis of building envelope parameters for two historical classroom designs, the Avalon and Canterbury blocks (constructed between 1955 and 2000). Optimise window-to-wall ratios, ceiling heights, window placement, insulation values (R-values), clothing insulation (Clo), and window opening schedules. Our findings demonstrate that strategic modifications to the building envelope can significantly improve occupant comfort and energy performance. Specifically, increasing ceiling height by 0.8 meters, raising windows by 0.3 meters vertically, and reducing the window-to-wall ratio to 25% created optimal conditions across multiple performance criteria. These targeted adjustments improved adaptive thermal comfort, ventilation, carbon dioxide, and energy efficiency while maintaining local and international standards compliance. The implications of the findings extend beyond the studied classrooms, offering evidence-based strategies for overall design and building performance guidelines in educational facilities. This research demonstrates the efficacy of applying computational design optimisation during early design phases, providing policymakers and architects with practical solutions that could inform future revisions of New Zealand's school design standards and align them more closely with international best practices for educational environments.

Key Words: Classroom design, indoor air quality, energy efficiency, thermal comfort, parametric modelling, OECD standards

5.1 Introduction

Optimising indoor air quality (IAQ) and thermal comfort while managing energy consumption is a critical design objective for school buildings. Creating a healthy indoor environment in educational facilities presents unique challenges due to the complex interplay of various factors (Graca et al., 2007). Research has consistently demonstrated that IAQ and thermal comfort parameters significantly impact the learning process, educational outcomes and health parameters (Barbhuiya & Barbhuiya, 2013; Zhang et al., 2017). Hence, indoor air quality (IAQ) and thermal comfort are taken as significant factors of indoor environmental quality (IEQ) in overall designing and constructing educational spaces (Fathi & O'Brien, 2023).

Educational spaces, particularly classrooms where students and teachers spend extended periods, are crucial in shaping the learning environment. The key elements of IEQ, including lighting, thermal conditions, acoustics, and air quality, have been shown to influence educators' and students' well-being, satisfaction, and performance (Zahiri & Altan, 2016). For instance, suboptimal air quality conditions or thermal discomfort can negatively affect concentration, engagement, and overall academic achievement. Building envelope design, especially the configuration and placement of windows, is fundamental in achieving desirable indoor environments while contributing to energy efficiency. Windows not only provide natural light and views but also impact thermal performance and ventilation (Ochoa et al., 2012). Numerous studies have explored the relationship between IAQ and thermal comfort and their association with educational outcomes, particularly emphasising classroom environments. These spaces, designed for prolonged occupancy and focused learning activities, require careful consideration of environmental factors to create conditions conducive to effective teaching and learning (Puteh et al., 2012). The critical aspects of IEQ in educational settings are indoor air quality and thermal comfort, encompassing both natural and artificial sources (Küller & Lindsten, 1992). Proper indoor air quality and thermal comfort have been associated with various benefits, including improved mood, enhanced motivation, and reduced fatigue(Edwards & Torcellini, 2002). Some researchers suggest that well-designed IEQ strategies can positively influence students' ability to absorb and retain information, potentially leading to improved academic performance (Ochoa et al., 2012).

The design of educational spaces, particularly classrooms, represents a complex process that demands careful consideration of multiple environmental factors and their interactions. The architectural design process encompasses multiple stages and involves diverse stakeholders, creating a complex web of interactions among architects, consultants, facility operators, and end-users. Ensuring environmental quality requires continuous refinement of design methodologies. Contemporary architectural education integrates multidisciplinary approaches, combining engineering, environmental psychology, and building science insights to enhance understanding of environmental comfort and its practical applications in design (da Graça et al., 2007).

In designing educational spaces, substantial efforts are being made to create high-quality learning spaces. Collaborative endeavours aim to develop high-performance classrooms in many technologically and economically advanced countries. These classrooms prioritise occupant health by improving indoor air quality, thermal comfort, visual, acoustics and the performance of students and teachers while also considering environmental impact and cost-effectiveness (Frelin & Grannäs, 2021). However, in developing countries, many recent advancements in ensuring high performance and quality in the school environment have not been integrated into the design process of educational spaces. In particular, evaluation procedures are often missing (da Graça et al., 2007). In most parts of the developing world, the quality of school building design mainly depends on established design criteria, professional knowledge and practice, and feedback from building performance assessments. The design process is typically carried out in traditional, linear ways, lacking important analysis phases (Pereira et al., 2018).

The significance of indoor environmental comfort in enhancing work and study productivity and student learning is widely recognised and largely determined by the educational spaces' design and adaptability to individual behaviours (Andargie & Azar, 2019; Brink et al., 2023). The extensive literature on school building design explores the relationship between school architecture and educational theory and trends, often through analysing exemplary designs and their impact on fostering a high-quality learning environment(Upitis, 2009). Research on school performance, including achievement rates, has examined various factors such as students' socio-economic background, school starting age, teaching methods, curriculum, and infrastructure (Andargie & Azar, 2019; Chen et al., 2020). Moreover, studies on school buildings have demonstrated that indoor environmental comfort factors can significantly influence the learning process.

Research conducted in 2002 for educational spaces identified a significant link between student academic performance and multiple facets of the indoor educational setting. It revealed that enhanced building conditions, such as modern construction, improved lighting, optimal temperature control, and high air quality, can positively correlate with better student outcomes. Additionally, the study examined the influence of school size on student achievement, highlighting that smaller occupancy in schools tends to create a more secure and engaging environment, reduce disciplinary problems, and enhance satisfaction among stakeholders, including families, students, and teachers. The report further supported these findings by noting that class sizes with a student-teacher ratio of 15:1 or lower are associated with improved performance in mathematics and reading and positive behavioural impacts (Schneider, 2002).

The design of educational spaces typically draws upon conventional design principles, professional knowledge, and feedback from past experiences rather than employing systematic methodologies and in-depth analyses. As a result, the design quality can vary significantly, often contingent upon the individual designer's expertise and experience, and may inadvertently marginalise considerations for indoor environmental comfort (López-Chao et al., 2020). The design phase frequently overlooks the investigation and assessment of various comfort solutions. Despite ongoing efforts to improve school building design, many public schools fail to provide adequate learning environments, primarily due to inconsistent architectural standards. Moreover, using simulations and optimisation techniques in design evaluations is rare, user engagement is typically absent from the design process, post-occupancy evaluations (POEs) are seldom carried out, and building performance data are not effectively incorporated into subsequent designs (Barrett et al., 2013).

Primary school educational spaces occupy a foundational role in the developmental journey of children, being compulsory in most countries, and thus involve a significant amount of time spent in school settings (Arya et al., 2024). As a result, a comprehensive analysis of the school environment is essential for grasping the elements that impact student learning, health, and overall well-being (Arya et al., 2023). Student health, including physical, psychological, and emotional aspects, is crucial for effective learning and personal development. Concurrently, academic achievement, which is evidenced through grades, assessment results, classroom engagement, and a thorough understanding of the curriculum, reflects a student's educational progress and accomplishments (Toyinbo, 2023). Additionally, similar to other developed countries from worldwide, New Zealand has also significantly improved its minimum mandatory IAQ and TC requirements after recent challenges posed by COVID-19.

The fact that natural ventilation systems are present in around 90% of New Zealand primary schools highlights the necessity of strict Indoor Air Quality (IAQ) and Thermal Comfort (TC) standards. These standards aim to ensure learning environments that can support a variety of teaching methods and learning activities. The COVID-19 pandemic, which arrived in New Zealand in February 2020, led the Ministry of Education (MOE) to update the DQLS V2.0 in 2022. This revised version emphasises the importance of ventilation in reducing the spread of airborne diseases, including COVID-19. The updated DQLS 2.0 includes more stringent requirements for fresh air intake and distribution, specifying increased air change rates (ACH) or ventilation rates (L/s/p) and lower carbon dioxide concentrations (ppm). Additionally, it offers improved guidance for heating and cooling, with temperature recommendations adjusted to suit specific regional climates. Design verification and compliance procedures have also been enhanced, with mandatory building performance modelling required for larger buildings with a higher window-to-wall ratio (WWR). Lastly, the updated guidelines encourage the use of indoor environmental monitoring tools in every classroom to continuously assess the effectiveness of ventilation systems (Arya et al., 2024).

In New Zealand, the Ministry of Education (MOE) has formulated the Designing Quality Learning Spaces (DQLS) document to direct the development of suitable indoor environmental quality (IEQ), which includes indoor air quality (IAQ) and thermal comfort, within New Zealand's classrooms and learning areas. The DQLS is intended to foster optimal learning environments in new school constructions. Initially released in 2007 as separate documents for IAQ and thermal comfort, these guidelines were amalgamated and revised in 2017 (version 1.0). A further update in 2022 (version 2.0) introduced new benchmarks for air quality, thermal performance, heating, and ventilation within classrooms. DQLS 2.0 also delineates mandatory air quality, temperature, thermal performance, and indoor environment monitoring stipulations. These reinforced mandatory requirements in the updated DQLS 2.0 correspond with the MOE's 2030 School Property Strategy. This strategy accentuates student well-being and creates high-quality learning spaces accommodating diverse teaching and learning approaches. The DQLS 2.0 update mirrors the evolving context of educational space design and commissioning, which is now overseen by regulatory bodies (Ministry of Education, 2022).

There is a general agreement among researchers and designers on the importance of IAQ and thermal comfort in improving the indoor environmental quality of educational spaces. They also acknowledge the challenge of balancing multi-individual factors and benefits with reducing discomfort to user activities (Fathi & O'Brien, 2023). As a result, careful design of building envelopes, with a focus on passive design strategies where possible, is crucial (Ochoa et al., 2012). Research has shown a strong link between the indoor environmental conditions in educational buildings and their architectural and constructional features. These features include layout, orientation, spatial arrangement, thermal envelope properties, window-to-wall ratios, and external shading (Fathi & O'Brien, 2023; Tabadkani et al., 2018). In New Zealand, through the DQLS V 2.0), the Ministry of Education prioritises healthy classrooms by emphasising improved indoor air quality and thermal comfort. These DQLS requirements, which also cover acoustics and lighting, call for a comprehensive design approach. Given the complex interplay of variables within indoor environmental quality (IAQ, thermal comfort, acoustics, and lighting), designers must consider their combined effects during both the design and commissioning phases to ensure an optimal learning environment (NZ Ministry of Education, 2022; Tran et al., 2023).

Hence, New Zealand's commitment to incorporate best practices in sustainable educational spaces is well reflected in the Designing Quality Learning Spaces (V2.0) document. However, the efficacy of these guidelines in ensuring optimal building performance, particularly in the face of the nation's diverse climate zones, warrants thorough investigation. Furthermore, a direct comparison with internationally recognised standards is essential to benchmark DQLS (V2.0) and identify potential areas for improvement. Building upon the findings of our prior research (Arya et al., 2023; Arya et al., 2024), which analysed the textual content of DQLS (V2.0) and international standards, this study employs building performance simulation to evaluate the practical impact of these differences on classroom performance.

The study aims to ascertain the suitability of current IAQ and Thermal Comfort guidelines in DQLS (V2.0) compared to OECD standards and design optimal post-COVID-19 IAQ and TC design guidelines for New Zealand Primary schools. Achieving the above aim is further categorised into two individual objectives: RO1. Simulate the IAQ and TC design guidelines from DQLS (V2.0) and OECD standards to identify limitations and appropriateness for post-COVID-19 primary school classrooms in six climate zones of New Zealand. RO2. Design and compare the optimal IAQ and TC guidelines for post-COVID-19 with OECD standards.

Henceforth, assessing indoor environmental quality in educational spaces requires a holistic approach incorporating multi-criteria optimisation of indoor air quality (IAQ) and thermal comfort (TC) factors, as established guidelines maintain. A key component of this approach is Building Performance Assessment (BPA), which uses computational models to forecast and analyse building performance across various aspects. BPA employs simulation to evaluate airflow patterns for IAQ, assessing ventilation effectiveness. For TC models, heat transfer and occupant comfort consider temperature, humidity, and radiant heat. During the design phase, simulation software thoroughly evaluates diverse design parameters, including ventilation strategies, material selection, and building envelope. The energy assessment enables the calculation of heating and cooling loads along with infiltration and natural ventilation loads. This allows designers to explore scenarios and their impact on IAQ metrics, such as carbon dioxide concentration and ventilation effectiveness, and TC indicators, like Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD). Simultaneously, the design process incorporates relevant IAQ and TC standards and guidelines, ensuring simulated performance aligns with recommended benchmarks. This iterative process, which integrates simulation-driven insights with guideline adherence, results in classroom designs that meet and exceed performance expectations for both IAQ and TC, creating healthier and more productive learning spaces.

BPA offers a quantitative framework for evaluating the effects of design choices on IAQ and TC design guidelines (Preiser & Vischer, 2006). Using simulation allows designers to test various design options before construction, thus avoiding costly rework. For example, different ventilation system layouts can be simulated to determine the most effective strategy for fresh air delivery and carbon dioxide concentrations. Similarly, the influence of window placement and shading devices on daylighting and solar gain can be evaluated to optimise thermal comfort and minimise energy use. BPA also aids in identifying potential issues, such as stagnant air pockets or areas of excessive heat gain, enabling proactive solutions during design. This proactive approach, facilitated by BPA, significantly contributes to creating high-performing classroom environments prioritising occupant well-being and learning outcomes (da Graça et al., 2007).

5.2 Materials and Methods

A building performance assessment (BPA) using a parametric modelling approach is used to optimise the architectural design features of school classrooms. BPA used in this study focuses on IAQ, thermal performance, energy efficiency and daylighting assessment. Classroom reference buildings, i.e. existing blocks (Avalon and Canterbury), were used as the basis for the detailed parametric analysis in six climate zones of New Zealand. The multi-criteria optimisation for optimal IAQ, TC, ventilation strategy and carbon dioxide variables were chosen as Temperature (°C), relative humidity (%), PMV scale, clothing insulation (clo), R-value (°C·m²/W), ventilation type, Air change per hour (ACH), outdoor airflow (l/s/p), carbon dioxide concentration (ppm), occupancy schedule, number of occupants (n), classroom size (m2). The following parameters were assessed from BPA to develop the optimal IAQ and

TC. Heating load & cooling load (kWh/m2), infiltration load & natural ventilation load (kWh/m2), daylight analysis (lux %) and illuminance, climate data file (EPW file), dew point and dry bulb temp (℃), building typology, construction type, year of construction, and window-to-wall ratio (WWR%). An evolutionary computation via the ladybug tool (LBT) was followed in correlation to the Honeybee (HB) plug-in for Grasshopper (GH)/Rhino, which was used to optimise (Ladybug Tools, 2024). The study is divided into four main parts: (1) classroom typologies (Avalon & Canterbury block) modelling in Rhino 7 software, (2) development of GH classroom reference model, (3) performance analysis of case study building typologies (IAQ, TC, DA & Energy analysis), and (4) parametric optimisation DQLS (V2.0) and international standard set by OECD countries in six climate zones of New Zealand.

In the first step, as per design features, Avalon and Canterbury's blocks were modelled in the Rhino 7 software, keeping all the construction details for the building envelope (roof, walls/cladding, floor/foundations, year of construction) along with windows and door similar to the actual reference modelled in the documents (Ministry of Education, 2013a, 2013b). In the second step, the Grasshopper plugin developed the script for connecting the Avalon and Canterbury block's design attributes to analyse the simulation steps. The Grasshopper script consists of several individual designing attributes, such as a classroom design envelope connected with the climate data file. In the third step, Ladybug and Honeybee tools were used from the database of the Grasshopper plugin to simulate thermal comfort, daylight analysis, energy analysis, ventilation and carbon dioxide for DQLS (V2.0) in six climate zones of New Zealand. Later, ASHRAE 62.1, CIBSE, EN – 15251, and BB (99 & 101) international standards were simulated individually in six climate zones of New Zealand. All the tools and plugins were run individually to minimise the bug error of margin for holistic analysis of multi-criteria optimisation until the complete script runs without showing any margin of error. DQLS (V2.0) and international standards simulation were performed to identify the limitations and appropriateness of current IAQ and TC guidelines in both New Zealand primary school classroom typologies. In the fourth step, based on the findings from prior simulations and holistic engineered solutions (literature review), certain changes were adopted to Avalon and Canterbury block design features, such as increased ceiling height, window's vertical placement, changes in R-value and Clo insulation. Following the preparatory steps to the simulation assessment, the multi-criteria optimisation task was carried out to develop the optimal design guidelines for IAQ and TC in primary school classrooms for Post covid -19 in six climate zones of New Zealand, as shown in Figure 5.1 below.

5.2.1 New Zealand Climate Zones

New Zealand, situated in the South Pacific region, exhibits diverse climatic conditions. The nation is classified into six distinct climatic zones, as defined by the New Zealand Building Code (Jalali et al., 2023; Ministry of Business Innovation and Employment, 2022). Six of New Zealand's major urban centres, each representative of a specific climatic zone, were selected in case studies for Avalon and Canterbury Block parametric modelling. The accompanying figures 1&2 below illustrate the geographical placement of these cities and their respective climatic zones. This selection allows for a comprehensive assessment of building performance across the varied environmental contexts found within New Zealand.

Figure 5.1 explains each of the six climate zones of New Zealand, offering the type of weather conditions in both the summer season and winter seasons. In addition, each major urban city's exact latitude and longitude location. To better understand each climate zone location within two different islands, the North Island and South Island, refer to Figure 5.2 below. The selection of colour in Figure 5.1 is synced with Figure 5.2. Table 5.1 below gives an idea of the six climate zone abbreviations for the other sections of this chapter.

Figure 5.1: New Zealand's six climate zones with coordinates and temperature range

Source: (Jalali et al., 2023)

Table 5.1: Abbreviations for six climate zones of New Zealand

Climate Zone	Urban City’s
CZ1	Auckland (AKL)
CZ2	Hamilton (HAM)
CZ3	Wellington (WELL)
CZ4	Rotorua (ROTO)
CZ5	Christchurch (CHCH)
CZ6	Queenstown (QTN)

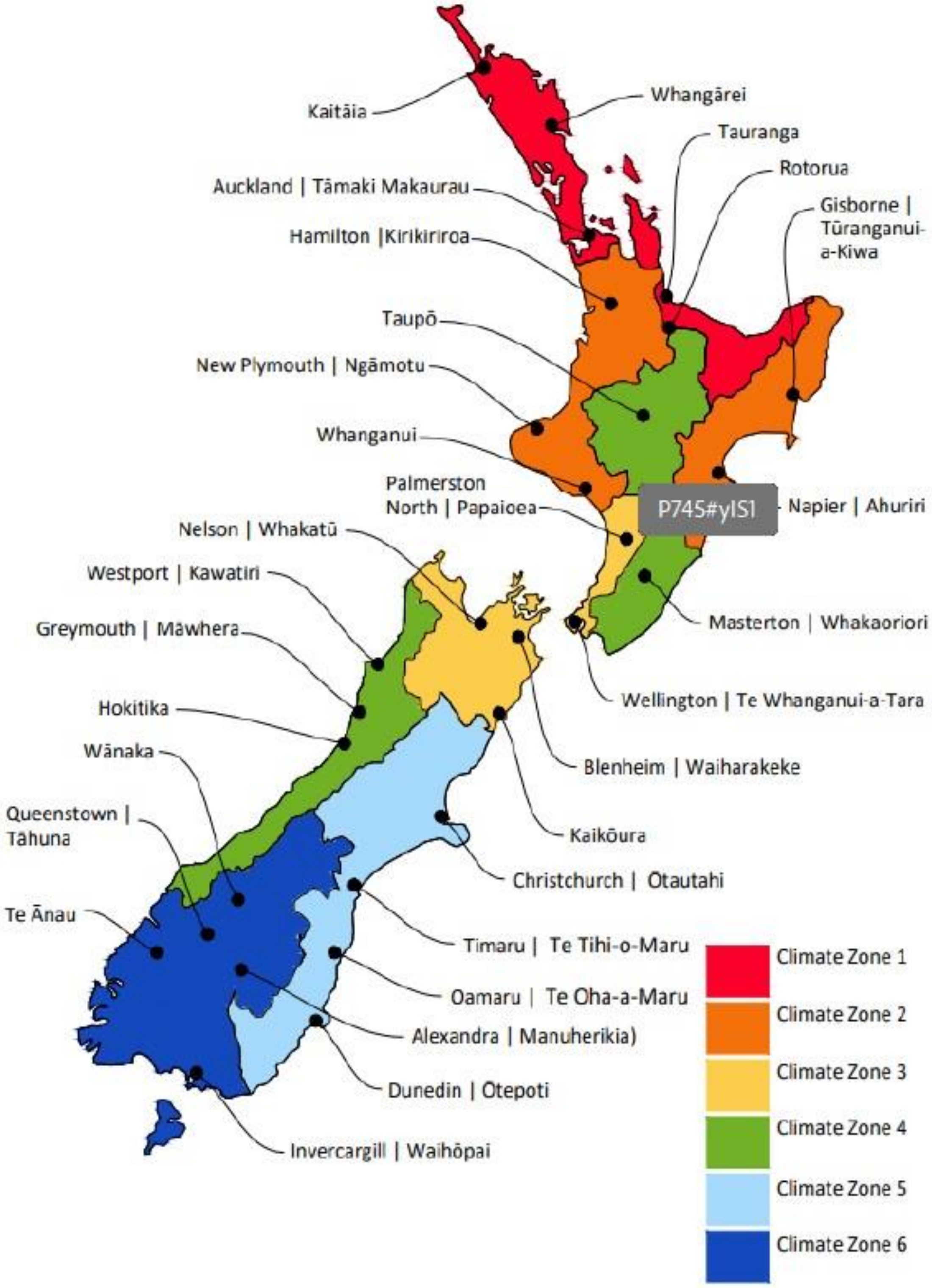

Figure 5.2: New Zealand Map (Climate Zones)

Source: (Ministry of Education, 2022)

5.2.2 Multi-criteria optimisation of building design

Recent advancements in building optimisation have highlighted the significance of evolutionary computation in addressing complex architectural challenges (Konis et al., 2016). This approach facilitates the identification of optimal or near-optimal solutions through systematic parameter variation within defined design constraints (Machairas et al., 2014; Qingsong & Fukuda, 2016). Parametric analysis enables early-stage performance evaluation across multiple design configurations, supporting enhanced energy efficiency outcomes while maintaining cost-effectiveness (Konis et al., 2016). The widespread adoption of computational design tools in architectural practice reflects their growing importance in addressing environmental challenges. Early-stage performance analysis enables practitioners and researchers to evaluate critical design parameters, including volumetric composition, spatial configuration, and envelope systems. This proactive approach optimises energy efficiency while maintaining cost-effectiveness throughout the design process. Integrating these analytical tools empowers designers to make informed decisions based on quantifiable performance metrics before significant resources are committed to development (Zhang et al., 2020).

5.2.3 Simulation Software Employed

Various simulation software is available worldwide, from comprehensive building analysis to specifically calibrated platforms designed for building performance simulations. A critical distinction exists between simulation engines, which process complex thermodynamics and building science calculations and modelling interfaces (Crawley et al., 2008). The IES - VE and Design Builder software have established an early grasp on architectural designing for early-stage construction (Weytjens et al., 2011). Notable among these is Rhinoceros, which leverages the Grasshopper plug-in ecosystem for energy simulation. This ecosystem's Ladybug

Tools (LBT) and Honeybee Tools (HBT) framework facilitates complete numerical building analysis by integrating Energy Plus and open foam (Darvishi Alamdari, 2022; Fathi & O'Brien, 2023; Lakhdari et al., 2021; Salamone et al., 2021; Wang et al., 2022; Ziaee & Vakilinezhad, 2022). Climate Studio, another Grasshopper-based application, offers comparable functionality to LBT through a streamlined interface without open-source accessibility. In contrast, Sefaira, integrated with Sketchup, provides basic functionality but lacks advanced modelling capabilities (Darvishi Alamdari, 2022).

A comparative analysis of the software in Figure 5.3 below reveals LBT's superior suitability for advanced building performance research used in this study. In Figure 5.3, the X-axis represents the point scale (zero to five), and the Y-axis represents the individual comparative parameters. Its distinctive features include comprehensive CO2 concentration analysis, sophisticated thermal comfort modelling, energy analysis, daylighting and robust parametric simulation capabilities functionalities not fully matched by Climate Studio, IES-VE, or Design Builder. The study employs Energy Plus as its core simulation engine. It enables detailed analysis of multiple building systems, including ventilation, carbon dioxide concentration, daylighting, energy loads and thermal comfort, supporting comprehensive building performance evaluation using the Grasshopper plugin. The detailed GH script for individual parameters analysis is listed below, followed by figures between Fig. 5.4 to Fig. 5.12.

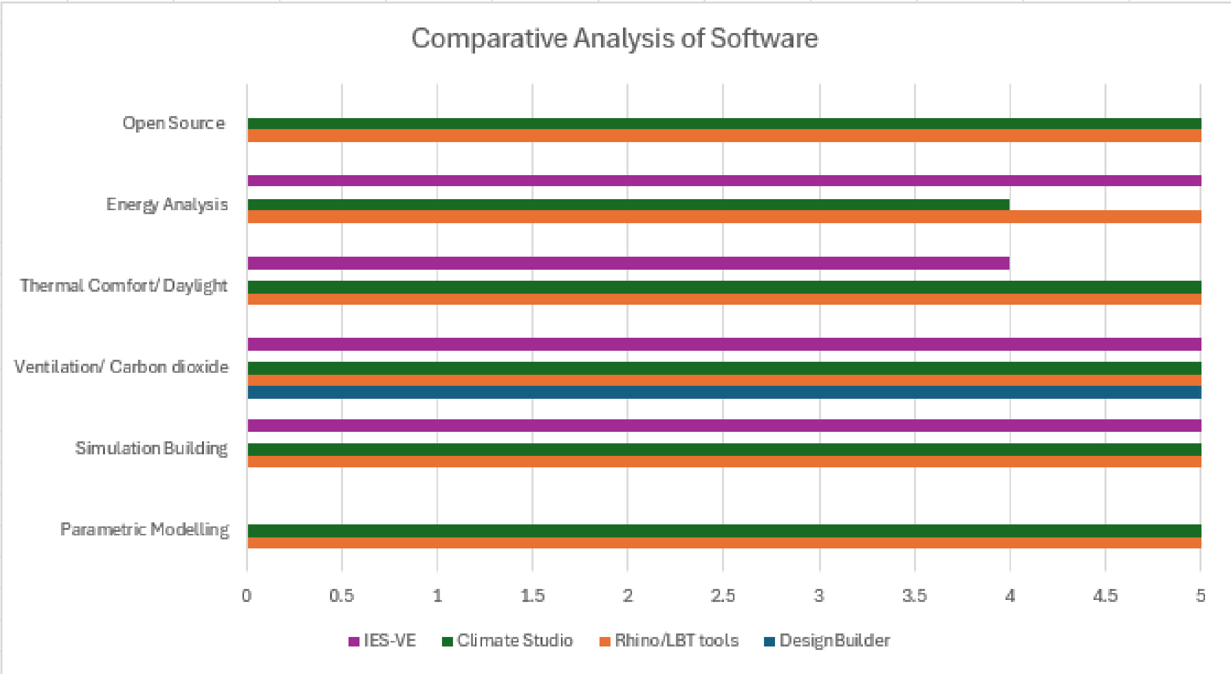

Figure 5.3: Comparative Analysis of Simulation Software

Source: (Darvishi Alamdari, 2022; Fathi & O'Brien, 2023; Lakhdari et al., 2021; Salamone et al., 2021; Wang et al., 2022; Ziaee & Vakilinezhad, 2022)

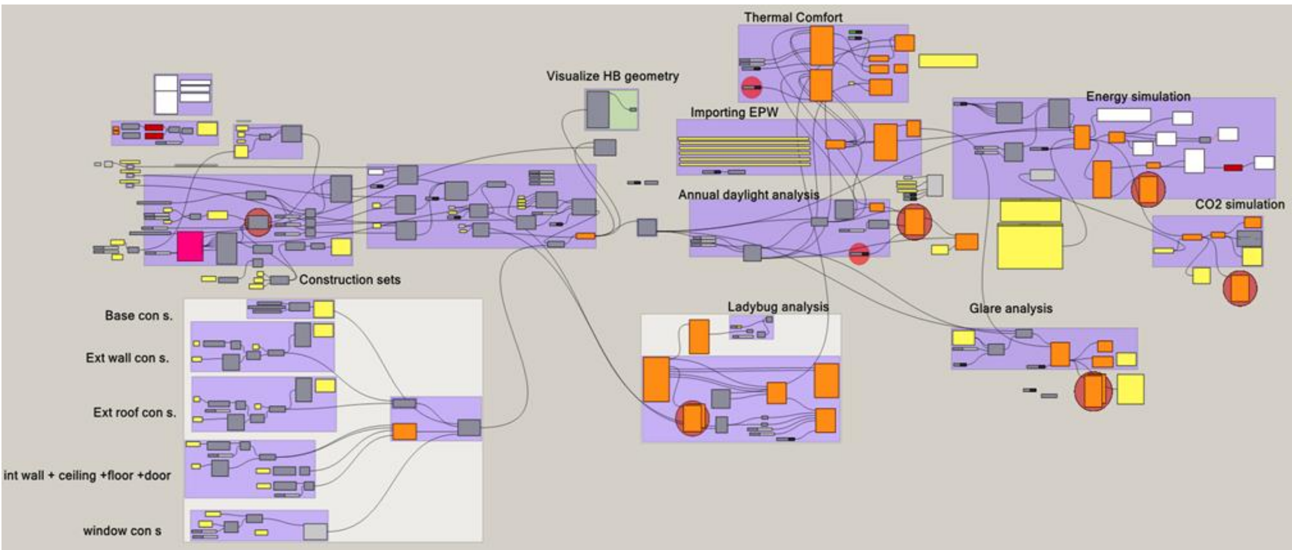

Figure 5.4: Grasshopper Script for Building Performance Assessment

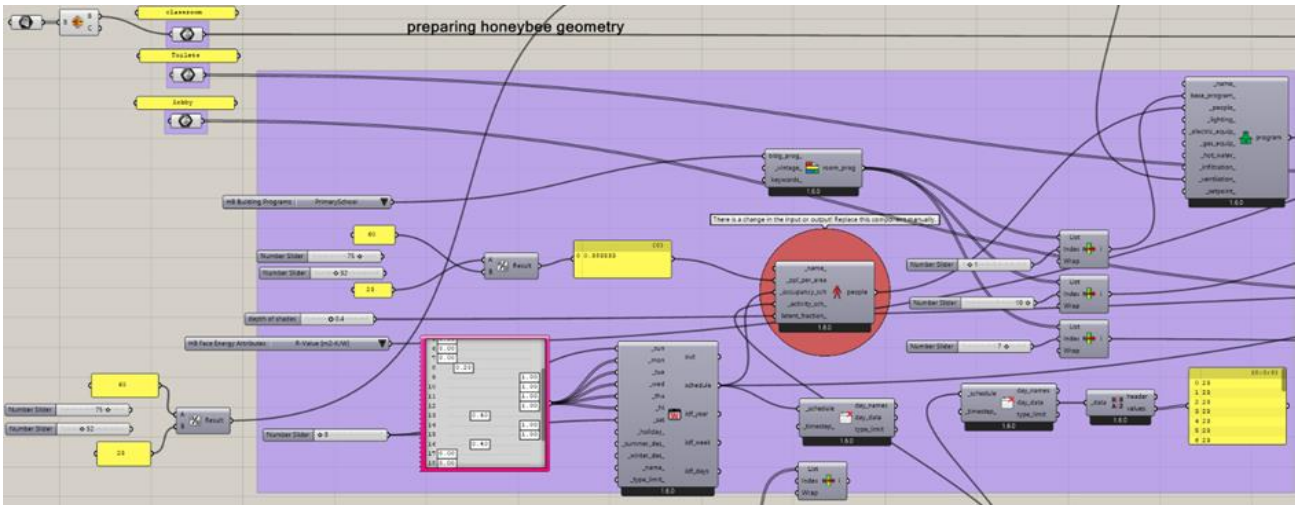

Figure 5.5: Grasshopper Script (Construction sets, Occupancy & Occupancy schedule)

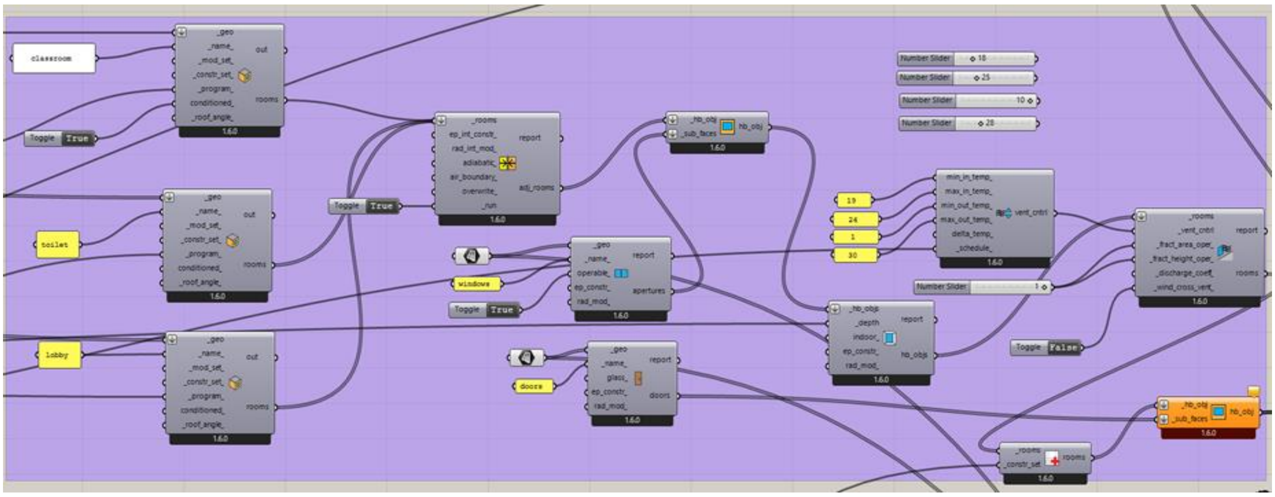

Figure 5.6: Grasshopper Script (Classroom modelling + Toilet + Lobby + Windows + Doors)

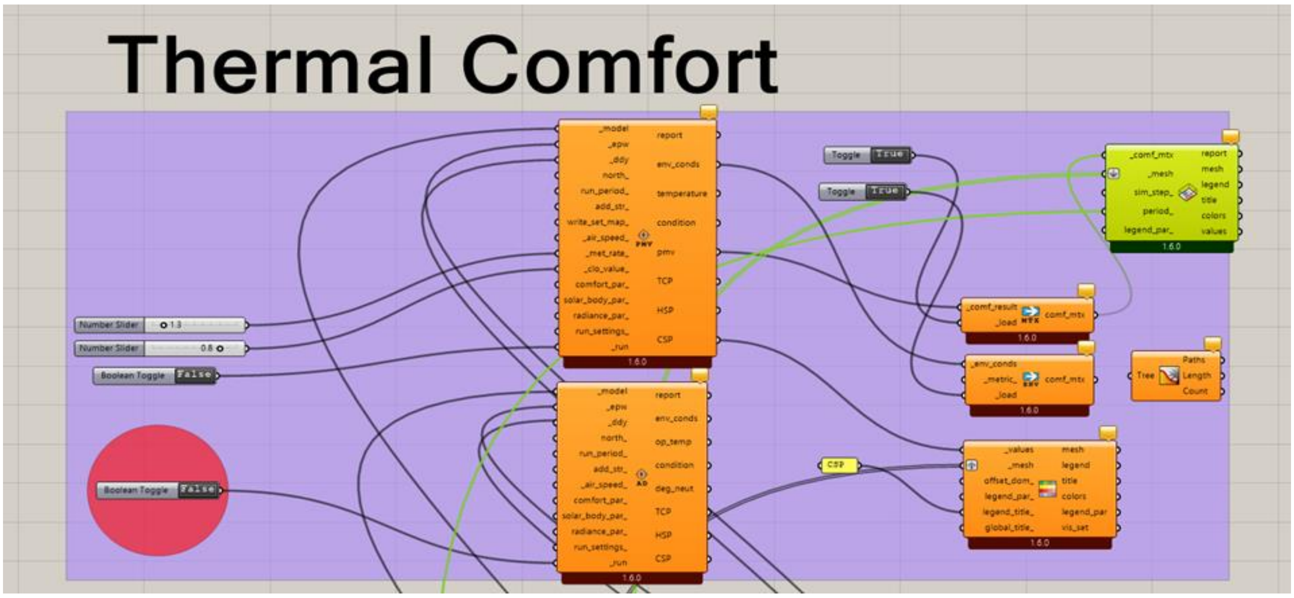

Figure 5.7: Grasshopper Script (Adaptive Thermal Comfort Analysis)

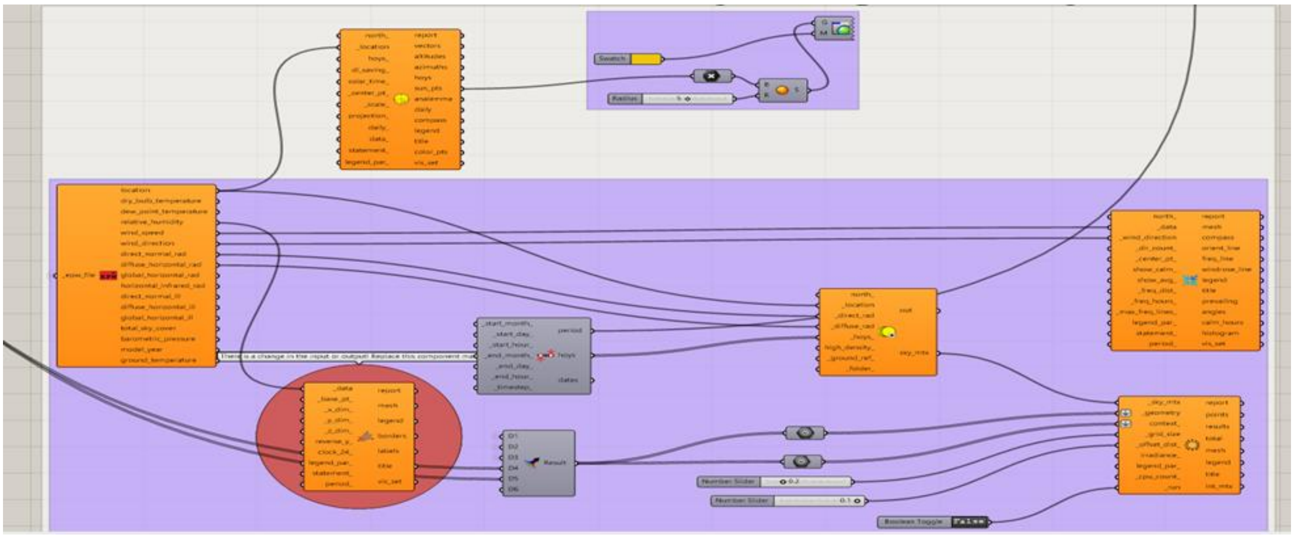

Figure 5.8: LBT (Relative Humidity, Dry bulb and Dew point temp)

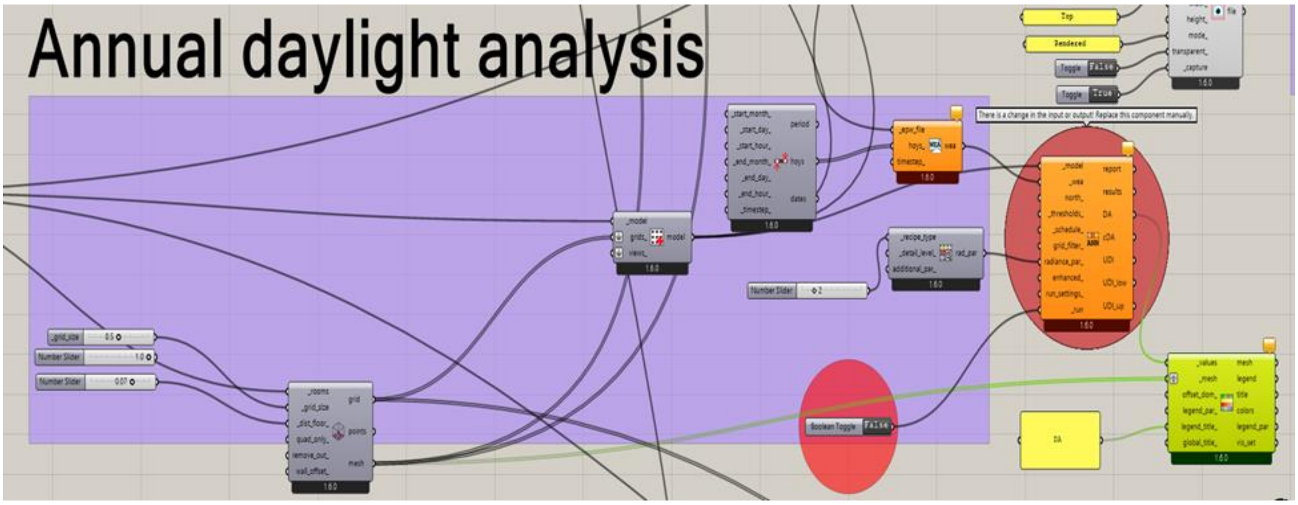

Figure 5.9: LBT (Daylight and Illuminance)

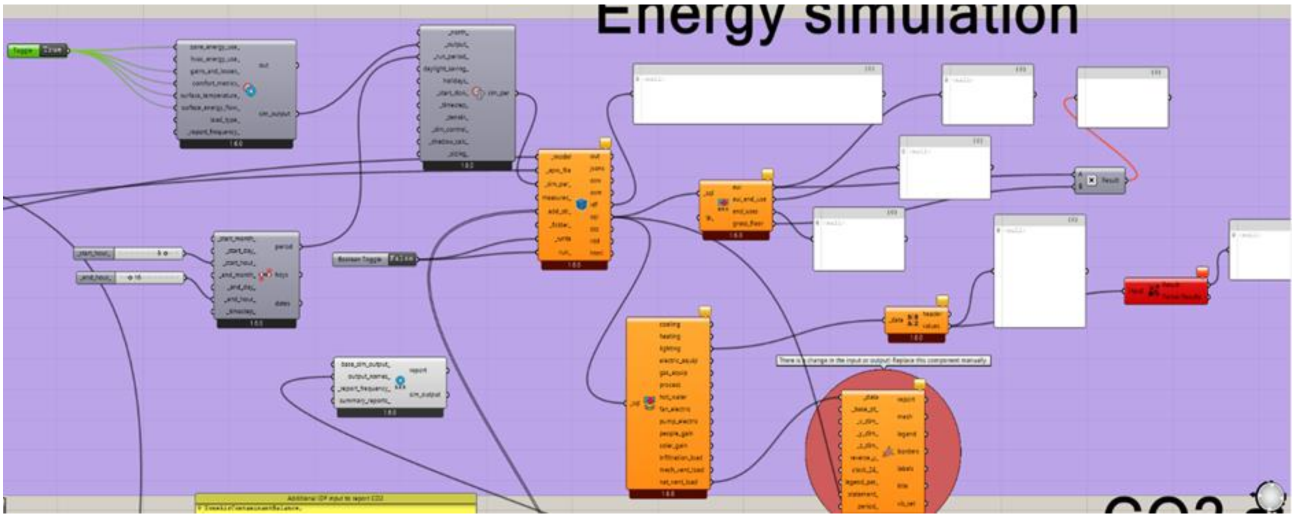

Figure 5.10: Grasshopper Script (Energy Analysis)

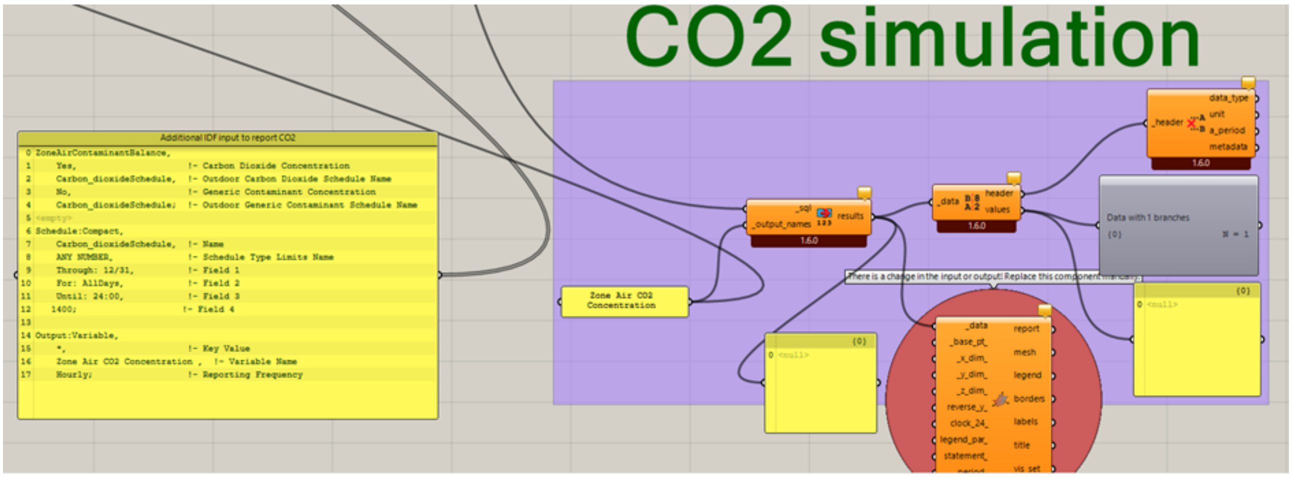

Figure 5.11: Grasshopper Script (Carbon dioxide Analysis)

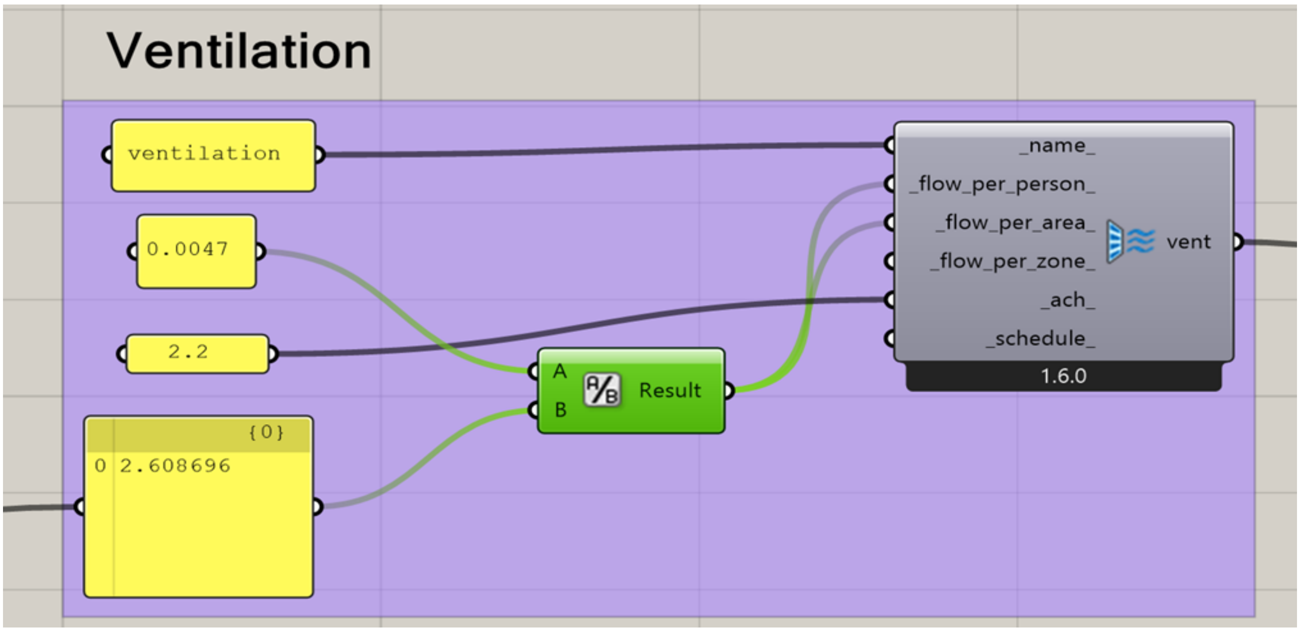

Figure 5.12: Grasshopper Script (Ventilation Rate)

5.2.4 New Zealand School Classroom Design Reference Models

A significant portion of New Zealand's primary school infrastructure, specifically 90% of current facilities, was constructed between the 1950s and 1960s (Swarbrick, 2012). These structures are primarily single-story, timber-framed buildings that rely on natural ventilation (Wang, 2020; Whitlock, 2008). They are characterised by large, single-glazed, operable windows that maximise ventilation and daylight penetration but lack thermal insulation. To address the dual challenges of increasing student enrolment and a shortage of educational facilities, the Ministry of Education (2017) has identified two main strategies: extending the lifespan of existing buildings and constructing new classroom spaces (Ministry of Education, 2017b; Wang, 2020).

This research employs a case study approach focusing on two representative school building typologies in New Zealand: the Avalon Block and Canterbury Block. These typologies were selected as they represent common architectural forms found throughout the New Zealand primary school building stock and serve as exemplary models for parametric optimisation analysis. Table 5.2 below shows the history of New Zealand Primary school building stock over time (Wang, 2020).

Table 5.2: History of New Zealand Primary School Building

Source: (Wang, 2020)

Time period	Classroom size	Construction and Material	Environmental Systems	Design features
Pre -1900	22 to 26 m2	Timber frame (lightweight, stone construction)	No specified systems for heating and aeration	Simple utilitarian design
1900 -1950	60 m2	Timber Frame building	Coal heating, no insulation, natural ventilation	Large windows (single-glazed), corridors as a cloakroom
1950 -2000	~75 m2	Relocatable modular classroom	Adopted low-level insulation, natural ventilation	Modular, relocatable Design classroom
2000 - present	85 m2 (20 m2 toilet & cloakroom)	Light timber frame building, carpet (floor), mandate thermally insulated	Sustainable design solution	Modern learning design (large open area), flexible breakout spaces

5.2.4.1 Avalon Block (Reference Primary school design)

Built predominantly between 1955 and 1962, Avalon school blocks are renowned for their durable construction, structural soundness, resistance to weather, and flexibility to accommodate changing educational requirements. A typical Avalon unit is a single-story building with cloakrooms at the back of the classrooms, providing access to nearby toilet facilities. These classrooms are characterised by large, nearly floor-to-ceiling windows on the front facade and clerestory windows along the rear. The clerestory windows create distinct high and low ceiling areas within the classroom. Avalon blocks can be found in various configurations, ranging from single classrooms to multi-classroom setups of up to four consecutive units. Table 5.3 below overviews Avalon block construction details (Ministry of Education, 2013a). The Figures (13 – 14) below give an idea of the standard view for built Avalon blocks and floor plans retrieved from the official Ministry of Education website.

Table 5.3: Avalon Block Construction Details

Source: (Ministry of Education, 2013a)

Avalon Block	• Constructed between 1955 and 1962 • 4 classrooms laid end to end • Concrete foundation walls • Roof covering consists of corrugated steel • Light timber framing • Clerestory windows running across the rear • Large classrooms with good natural cross-ventilation • Significant solar gain from large north-facing windows • L*W*H* = 9.6*7.2*2.7

Figure 5.13: Front View (Avalon Block)

Source: (Ministry of Education, 2013a)

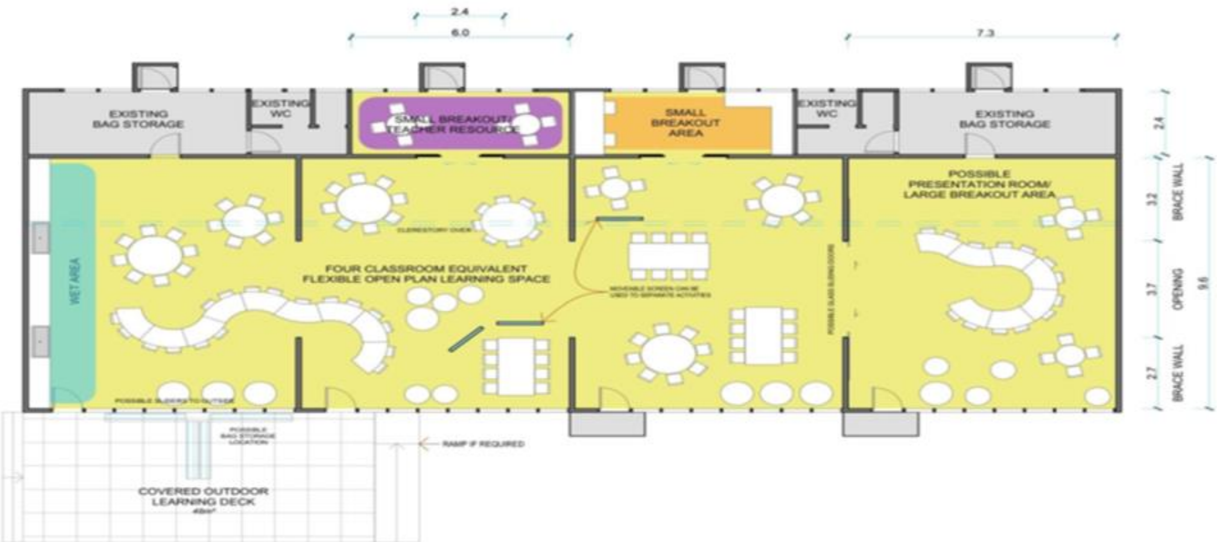

Figure 5.14: Layout (Avalon Block)

Source: (Ministry of Education, 2013a)

5.2.4.2 Canterbury Block (Reference Primary school design)

The Canterbury school blocks, constructed primarily between 1959 and 1965, are notable for their robust engineering. A standard Canterbury unit features a distinctive single-story design with a slight mono-pitch roof and integrated storage areas at the sides of the classrooms.

These classrooms are distinguished by their expansive north-facing windows that maximise natural light. They are complemented by smaller, strategically placed windows on the southern elevation to facilitate cross-ventilation without creating unwanted glare or heat loss. Canterbury blocks typically incorporate a covered exterior walkway along the northern facade, providing weather protection while maintaining outdoor connections. Table 5.4 below provides an overview of details of the construction of the Canterbury Block (Ministry of Education, 2013b). The Figures (15 – 17) below give an idea of the standard view for the Canterbury block and floor plans retrieved from the official Ministry of Education website.

Table 5.4: Canterbury Block Construction Details

Source: (Ministry of Education, 2013b)

Canterbury Block	• Ridged centrally along the building length. Corrugated steel roof • Light timber framing. Cladding (walls) masonry concrete block • Concrete slab on grade (floor) • Constructed From 1959 to 1965 • Large, glazed walls to the north and a large south window next to the toilets • Large classrooms with good natural cross-ventilation • Significant solar gain from large north-facing windows • L*W*H* = 9.6*7.6*2.7

Figure 5.15: Front View (Canterbury Block)

Source: Ministry of Education. 2013b)

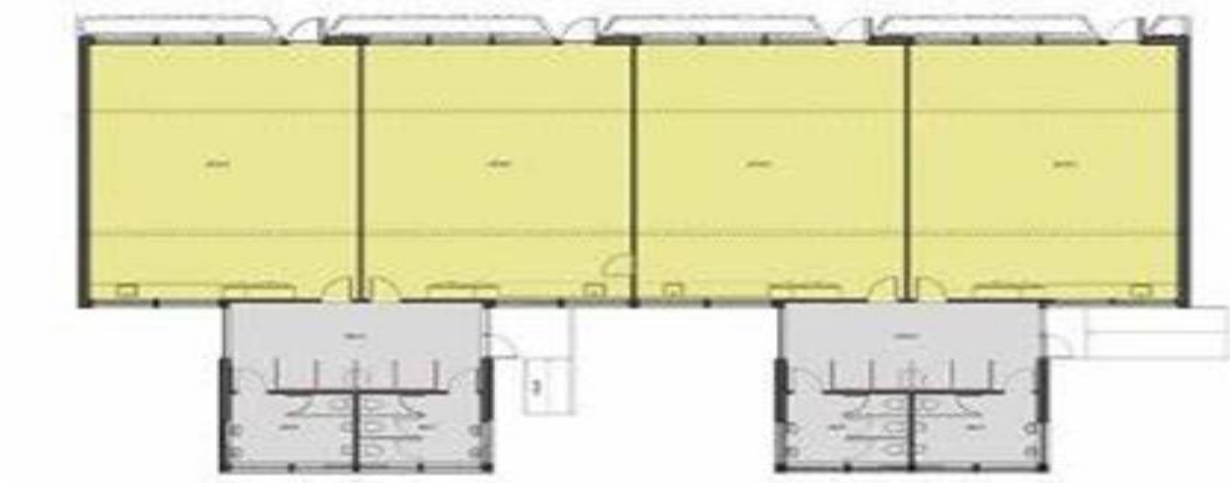

Figure 5.16: Design (Canterbury Block)

Source: (Ministry of Education, 2013b)

Figure 5.17: Overview (Canterbury Block)

Source: Ministry of Education, 2013b)

5.2.5 New Zealand requirements for thermal resistance of building components

Prior to 2017, educational spaces lacked dedicated insulation standards within these regulatory frameworks, resulting in the application of residential building criteria to school construction projects. Thermal insulation regulations for residential structures are defined in the New Zealand Building Code (NZBC) clauses H1 Energy Efficiency and E3 Internal Moisture (Department of Building and Housing, 2011). As outlined in NZS 4218 Thermal Insulation -Housing and Small Buildings, residential buildings must adhere to specific thermal resistance values (R-values, measured in m^2K/W) (Standards New Zealand, 2009). This regulatory gap for educational buildings was addressed in 2017 when the New Zealand Ministry of Education published the Designing Quality Learning Spaces: Indoor Air Quality and Thermal Comfort guidelines (Ministry of Education, 2017a). This document establishes mandatory insulation requirements for educational facilities to support optimal learning conditions and safeguard occupant health. The provisions apply to all new school construction and renovation projects initiated after January 1, 2018. A comparison of the thermal resistance specifications for educational facilities under DQLS 2017 and residential buildings under NZS 4218 across New Zealand's diverse climate zones demonstrates the evolving approach to building thermal performance in educational settings (Ministry of Education, 2017a; Standards New Zealand, 2009; Wang, 2020). The Ministry has established minimum thermal resistance (R-values) requirements for various building components, as detailed in Table 5.5. These requirements are designed to balance heat retention during winter with the dissipation and exclusion of heat during summer. The specified R-values differ according to the climate zone classifications in Figures 5.1 and 5.2. These thermal resistance thresholds are based on the New Zealand Building Code Clause H1, Acceptable Solution H1/AS2 (1st Edition, 2021), which addresses energy efficiency standards for buildings with a floor area exceeding 300 m^2. For buildings with occupied spaces less than 300 m^2 or those governed by H1/AS1 parameters, the stricter thermal resistance values outlined in H1/AS1 are applied (Ministry of Business Innovation and Employment, 2021).

While most NZ school buildings constructed before the 1990s are likely to operate with minimal thermal insulation or complete absence in wall cavities and ceiling spaces (Ministry of Education, 2013b), efforts have been made to improve the design of these thermally inefficient classrooms. Contemporary insulation standards were implemented to establish thermally appropriate educational environments that accommodate diverse pedagogical approaches and student learning processes. The COVID-19 pandemic's arrival in New Zealand in February 2020 prompted the Ministry of Education to comprehensively revise the Designing Quality Learning Spaces guidelines (Ministry of Education, 2022), aligning with international responses to the crisis. This updated framework strengthens ventilation requirements to reduce the transmission risk of airborne pathogens, including the SARS-CoV-2 virus. The revised standards encompass multiple enhancements: increased ventilation rates measured by air changes per hour (ACH) or per-person fresh air supply (L/s/p) alongside reduced carbon dioxide concentration targets; climate-specific thermal control parameters; stricter verification protocols including mandatory environmental modelling for larger facilities with elevated window-to-wall ratios (WWR); and requirements for permanent environmental monitoring equipment in classrooms to verify ongoing ventilation performance. The New Zealand education authorities have adopted a comprehensive approach to learning space design that recognises indoor environmental quality as fundamental to educational outcomes. The DQLS framework addresses thermal conditions and air quality in conjunction with acoustic performance and illumination requirements, necessitating integrated design solutions. This multifaceted approach acknowledges the interconnected nature of environmental variables within educational spaces. It requires designers to evaluate their collective influence throughout the design and implementation processes to optimise conditions for learning (Arya et al., 2023; Arya et al., 2024). Table 5.5 below shows the updated mandatory minimum R-value for school buildings according to DQLS (V2.0) for improved thermal comfort performance used in parametric modelling for this study (Ministry of Education, 2022).

Table 5.5: Minimum R-value for Building Component

Source:(Ministry of Education, 2022)

Climate Zones	Building Components				
	Roof	Wall	Floor	Windows	Skylights
AKL (CZ1)	R 3.5	R 2.2	R 2.2	R 0.33	R 0.42
HAM (CZ2)	R 4.0	R 2.4	R 2.2	R 0.33	R 0.42
WELL (CZ3)	R 5.0	R 2.7	R 2.2	R 0.37	R 0.46
ROTO (CZ4)	R 5.4	R 3.0	R 2.4	R 0.37	R 0.46

CHCH (CZ5)	R 6.0	R 3.0	R 2.5	R 0.40	R 0.49
QTN (CZ6)	R 7.0	R 3.2	R 2.6	R 0.42	R 0.51

5.2.6 Experimental Data for Building Performance Assessment

In the wake of the COVID-19 pandemic, the design of educational spaces has gained significant attention, particularly in the context of the importance of healthy IAQ and TC standards. Building performance simulations for both Avalon and Canterbury blocks were carried out to assess the adequacy of current IAQ and TC guidelines for six climate zones in New Zealand. In addition, both school typologies were simulated against local and international standards such as (DQLS V (2.0), ASHRAE 62.1, EN-15251, CIBSE, Building Bulletin 99 & 101) in six climate zones of New Zealand. Through advanced parametric modelling assessment, the BPA for Avalon and Canterbury block critically evaluates existing IAQ and TC guidelines, identifies their limitations, and proposes optimised design standards tailored to New Zealand's varied climatic conditions. The proposed optimal IAQ and TC design guidelines for New Zealand in six climate zones with a specific focus on adaptability and applicability in a post-pandemic educational environment are based on multi-criteria optimisation and a series of simulations performed, as shown in Table 5.6 below. Furthermore, Table 5.7 represents the DQLS (V2.0) and international standard (ASHRAE 62.1, CIBSE, EN-15251, BB 99 &101) IAQ and TC standard data used to perform the parametric modelling to identify the building performance for the post-pandemic educational environment in Avalon and Canterbury block in six climate zones of New Zealand.

Table 5.6: Total Number of Simulation for BPA and Parametric Modelling

New Zealand DQLS (V2.0)	Thermal comfort, Ventilation, Carbon dioxide, Daylight	336 simulations
International standard ASHRAE 62.1 CIBSE EN-15251 Building Bulletin 99 & 101	Thermal comfort, ventilation, carbon dioxide, Daylight	112 simulations
Optimal Design Changes	R-value, clothing insulation, WWR, ceiling height and window height	28 simulations

Table 5.7: Comparison of IAQ and TC parameters (OECD Countries)

Source: (Arya et al., 2024)

OECD Standards	Temperature ℃	Carbon Dioxide (ppm)	Ventilation Rate (l/s/p)	Occupancy (numbers)	Occupants Density (m2)	Classroom Size (m2)
ASHRAE 62.1	22 ℃	1000 ppm	6.7 -7.4 l/s/p	25	4 m2	100 m2
CIBSE TM57	21 ℃	800 - 1000 ppm	10 -15 l/s/p	-	2 -4 m2	-

EN-15251	20 -24 °C	800 - 1400 ppm	5 -8 l/s/p	23	2 -3 m2	-
BB (99&101)	20 -25 °C	1500 ppm	8 -10 l/s/p	28	2.3 m2	70 m2
DQLS (V2.0)	18 -25 °C	800 - 2000 ppm	5 -10 l/s/p	30	-	~75 m2

5.2.7 Occupancy Profile Schedule

The occupancy profile of the analysed spaces is defined by several critical factors: the total number of occupants, the proportion of the occupied area allocated to students and teachers, and the occupancy schedule, which specifies the times when individuals are present in the space during weekdays presented in Table 5.8 below. School buildings home students and various services, such as daycare, kindergarten, nursery and primary teaching, each operating on different schedules. Certain staff members usually arrive before the students. While the metabolic rate for sedentary occupants is around 60 Watt/m² (ASHRAE 55, 2017), or 120 Watt/person in Energy Plus software (DoE, 2014). Although clothing insulation significantly affects occupant thermal comfort, this parameter is kept constant at 0.75 for this study, and the Carbon Dioxide generation rate is typically between 3.34 – 5.5 cm3/s (Korsavi et al., 2020). Occupancy per space, and occupants' timetable are based on the New Zealand primary school classroom context in Table 5.8. Metabolic rate, CO2 generation rate, and CLO are the most common data available as a constant value (ASHARE 55, 2017) in this type of building simulation.

Table 5.8: Details of Occupancy Schedule

Source: (Darvishi Alamdari, 2022; Ministry of Education, 2022)

Occupancy	30 students, two teacher
Occupancy per space	2.3 student/ m2
Metabolic rate	1 met
Clothing insulation	0.75
CO2 generation rate per child	3.6 cm3/s
Occupants timetable	9: 00 am to 3:30 pm (occupancy)
Activity level	120 Watt/person

5.3 Results and Simulation Analysis

This section explains Avalon and Canterbury block primary school classroom typologies building performance assessments using parametric modelling regarding thermal comfort and daylighting, energy analysis, and ventilation and carbon dioxide. Further delve into this section, which is categorised by explaining the performance evaluation metrics for each optimisation. Rhino 7 Software modelled Avalon and Canterbury Blocks reference design is depicted below.

A base case (references) for both Avalon and Canterbury blocks was modelled in Rhinoceros 7 3D modelling software per the official design features in the previous section methodology subsection 5.2.4 (New Zealand School Classroom Design Reference Models). The figures below (5.18 – 5.20) show the Avalon Block (Back view, Front view and side perspective view). Figures (5.21 – 5.24) show the views of Canterbury Block.

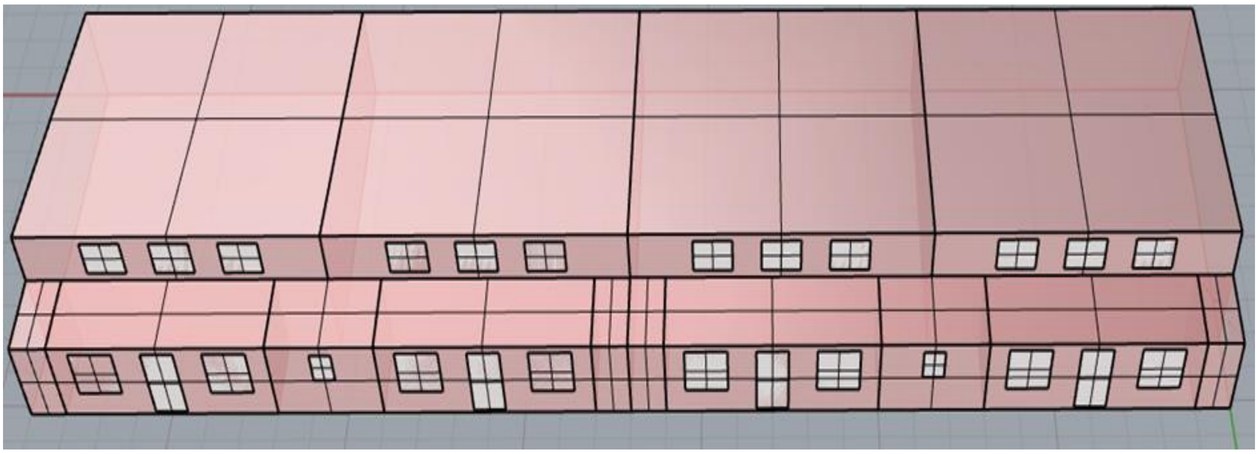

Figure 5.18: Avalon Block (Rear view- Rhino 7 Modelled)

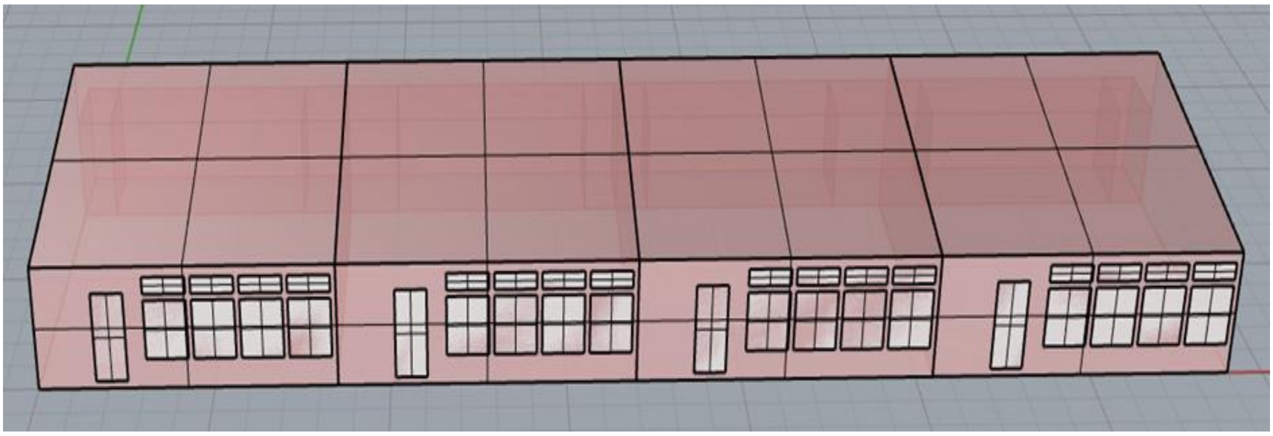

Figure 5.19: Avalon Block (Front View- Rhino 7 Modelled)

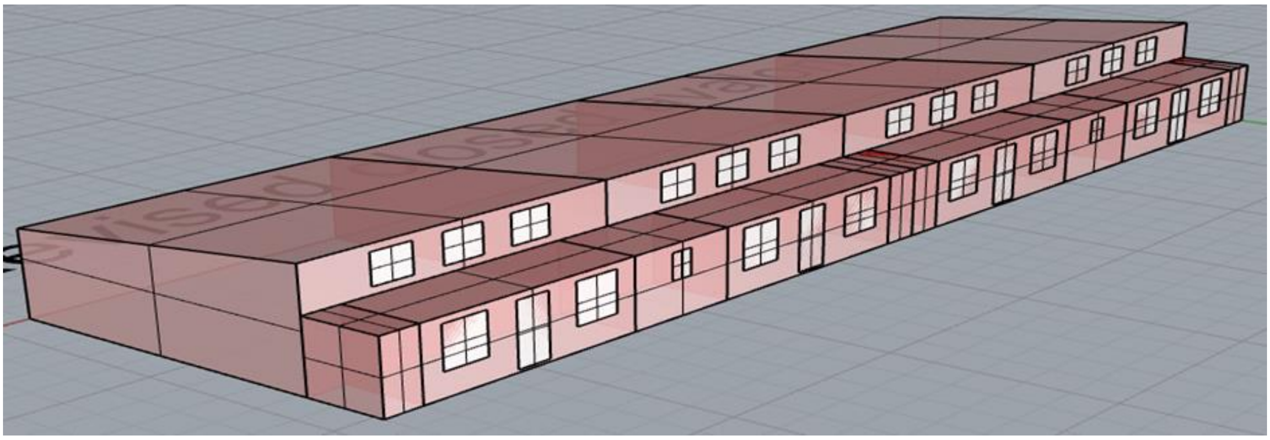

Figure 5.20: Avalon Block (Perspective View- Rhino 7 Modelled)

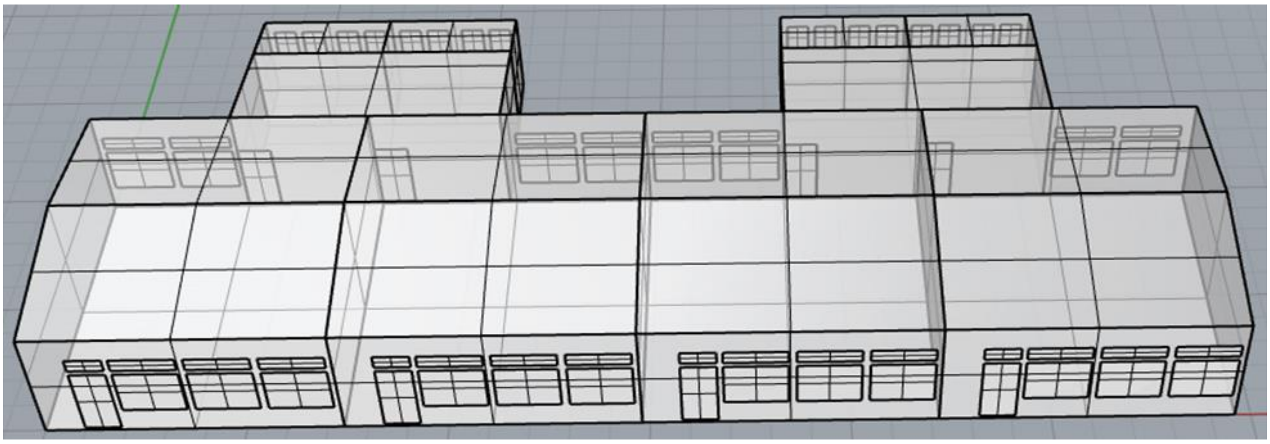

Figure 5.21: Canterbury Block (Front View - Rhino 7 Modelled)

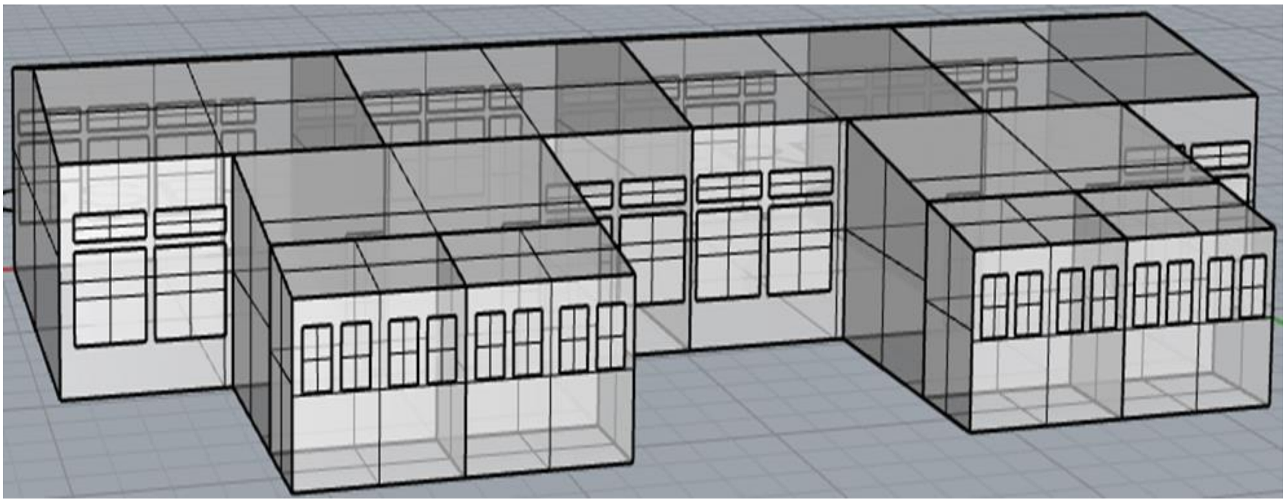

Figure 5.22: Canterbury Block (Rear view-Rhino 7 Modelled)

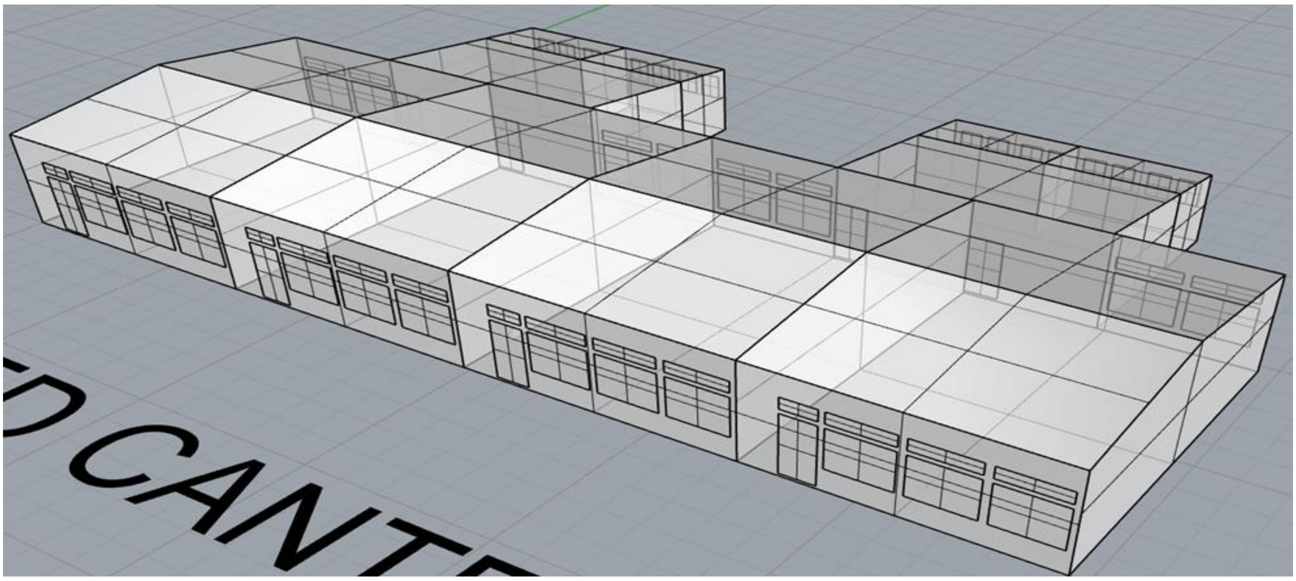

Figure 5.23: Canterbury Block (Perspective View - Rhino 7 Modelled)

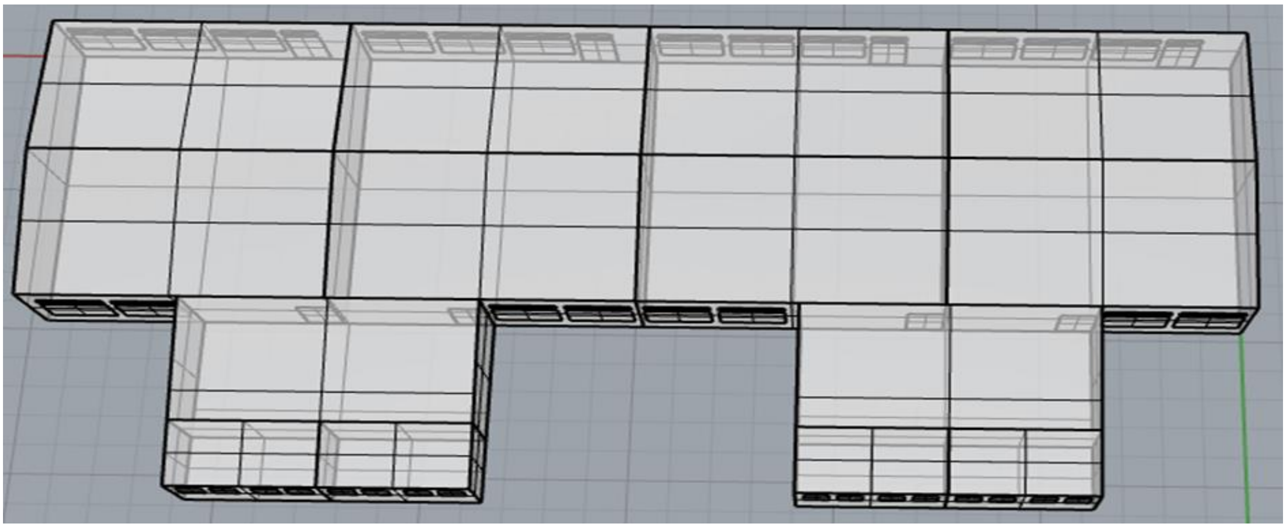

Figure 5.24: Canterbury Block (Top view - Rhino 7 Modelled)

5.3.1 Thermal Comfort and Daylighting Multi-criteria Optimization (MCO) Metric

Optimising the thermal comfort in any building requires significant consideration of multiple indoor environmental factors such as temperature, relative humidity, clothing insulation, and metabolic rate (Al-Absi et al., 2022). International standards have significantly developed thermal comfort standards worldwide to cater for individual satisfaction (Arya et al., 2024). Although there is a consensus on the significance of thermal comfort, differences emerge between children and adults in their subjective evaluations (de Dear et al., 2015). Children are more vulnerable to higher temperatures due to their elevated metabolic rates and the active nature of their school activities. This increased sensitivity highlights the need for meticulous attention to thermal comfort standards specifically designed to meet the needs of children in educational settings (Cheng & Brown, 2020). The thermal comfort standards are set to categorise the indoor environment and should offer comfortable conditions to the majority of occupants in the building. Henceforth, the international standard used in this study uses a similar strategy for thermally comfortable conditions via two main modelling options: A) PMV (predicted mean vote) scale & PPD (predicted percentage dissatisfied) scale; B) Adaptive PMV scale (Albatayneh et al., 2019; Arya et al., 2024).

PMV assumes a steady-state environment with limited occupant control. It may not accurately predict comfort in naturally ventilated buildings where occupants can adapt to varying conditions (e.g., by opening windows or adjusting clothing) (ASHRAE 55, 2013). Hence, the adaptive model to define thermal comfort in naturally ventilated buildings was created because it accounts for occupant behaviour and dynamic thermal conditions (Hoyt et al., 2013). Previous studies have underscored the importance of employing an adaptive method for precise thermal comfort assessment (Buratti & Ricciardi, 2009). Accordingly, this investigation adopts the Adaptive Comfort Percentage (ACP) as the principal measure for evaluating thermal comfort within classroom settings. The ACP is calculated using the Ladybug and Honeybee plugins for Grasshopper (Ladybug Tools, 2024). It indicates the percentage of occupied hours during which occupants feel thermally comfortable. Comfortable conditions are those where the indoor temperature remains within the acceptable range, which is determined by the current outdoor temperature. To examine the thermal comfort range for both Avalon and Canterbury school blocks, the findings are classified into three categories: Total Comfort Percentage (TCP), Heating Season Comfort Percentage (HSP), and Cooling Season Comfort Percentage (CSP). This method offers a detailed insight into the thermal comfort performance under various operational conditions.

The most common metrics described and assessed daylighting in indoor environments are useful daylight illuminance (UDI) and daylight autonomy (DA) (Lakhdari et al., 2021). For this study, we primarily focus on the natural light coming through the windows of both Avalon and Canterbury blocks in six climate zones of New Zealand. Adequate natural light minimises the energy load and is associated with indoor environmental comfort. Satisfactory natural light improves adults' and children's mood, performance, learning ability and physical health (Gago et al., 2015). Henceforth, UDI and DA are climate-based and accurate metrics that measure effective daylighting in indoor environments in different climate zones to indicate the percentage of yearly daylighting specifications (Li et al., 2021). The Useful Daylight Illuminance (UDI) metric measures the percentage of annual occupied hours when daylight illuminance is within a defined range (Mardaljevic, 2015). UDI acts as a dynamic measure of lighting performance, calculated based on illuminance levels at the work plane (0.75 meters above the floor), assessing the sufficient daylight (Sun et al., 2020). Daylight Autonomy (DA) evaluates the annual adequacy of daylight illuminance within an indoor space. Research indicates that spatial visual comfort and satisfaction are maximised when 50% of the analysed space achieves an illuminance level of 300 lux (Lakhdari et al., 2021; Pellegrino et al., 2017). The main factor contributing to the knowledge of this study for daylighting assessment is a window-to-wall ratio difference between both classroom typologies; Avalon is constructed with 70 m2 approx. 35 % of WWR (north-facing windows) and 73 m2 of the classroom for Canterbury has approx—30% of WWR (north-facing windows). The findings are classified into two categories to examine the natural daylighting comfort range for both Avalon and Canterbury school blocks: UDI percentage value and DA percentage value.

5.3.1.1 Thermal Comfort and Daylight (MCO) Simulation Result

Table 5.9. shows the adaptive thermal comfort percentage for both Avalon and Canterbury blocks simulated in six climate zones of New Zealand for all OECD standards depicted in Table 5.7. The classroom geometry and its content are iterated in Tables 5.3 and 5.4 for both Avalon and Canterbury blocks, followed by their respective figures and Occupancy details in Table 5.8 and envelope design features (thermal values) in Table 5.5. The simulation results are followed yearly, with time slots from 9 am to 3:30 pm and a weekly schedule from Monday to Friday. To calculate the adaptive thermal comfort percentage for both Avalon and Canterbury blocks, values for each OECD standard were put in the Grasshopper script connected with the Ladybug & Honeybee tools plugin see Fig. 5.7. The method creates a connection between the indoor and outdoor temperature by calculating the dry bulb

temperature, dew point temperature and relative humidity for all six climate zones see Fig. 5.8. The detailed simulation adaptive thermal charts are presented in supplementary file names (simulation outcomes). Per thermal charts, the colourful squares in the simulations show the percentage of occupied hours in both Avalon and Canterbury blocks according to OECD standards. The graphs with red-coloured square regions signify the achieved operative adaptive thermal comfort in both Avalon and Canterbury blocks. Satisfactory thermal comfort is achieved when most red squared boxes fall inside the classroom blocks.

The bottom of Table 5.9. shows the indoor daylighting percentage for both Avalon and Canterbury blocks simulated in six climate zones of New Zealand for DQLS (V2.0). The simulation timesteps are yearly based on a weekly schedule from Monday to Friday (9 am to 3:30 pm). The grasshopper script with ladybug and honeybee tools is specifically used to evaluate the daylighting run in coherence with the energy-plus simulation platform, as seen in Fig. 5.9. The output creates a link with greater exposure of WWR % to similar classroom size showed difference with not only daylighting percentage, but it also has significant impact with adaptive thermal comfort percentage in both classroom typologies. The detailed simulation charts of daylighting are submitted in the supplementary file (simulation outcomes).

5.3.2 Energy Performance Multi-criteria Optimisation (MCO) Metrics

The energy performance evaluation for both Avalon and Canterbury blocks in six climate zones of New Zealand for all OECD standards followed by a building performance assessment approach via parametric modelling. To better understand the energy performance evaluation, it is important to normalise the total building energy usage value in one metric, i.e., energy use intensity (EUI) (Borgstein et al., 2016). Primary contributors collectively represent 50 – 70% of total energy consumption in any building, which includes artificial lighting, heating, and cooling loads (Futrell et al., 2015). To evaluate energy performance effectively, this study employs annual energy use intensity (kWh/m²) measurements for each of these critical systems, following established methodological frameworks (Wang et al., 2020). This approach provides a comprehensive metric for quantifying and comparing the energy efficiency characteristics of the analysed building typologies.

5.3.2.1 Energy Performance (MCO) Simulation Result

Multiple factors, such as climatic conditions, heating and cooling loads, number of occupants, size of classrooms, and occupants schedule, affect the EUI metric. As EUI is a recognised metric for energy performance evaluation (Wang et al., 2012). This study evaluates the following loads (heating, cooling, infiltration, and natural ventilation) to assess the Avalon and Canterbury blocks in six climate zones of New Zealand for DQLS V (2.0) and international standards set by OECD countries. In the present study, HVAC systems were not considered in the simulation, as 90% of New Zealand primary schools rely on natural ventilation as the main source of air circulation (Wang, 2020). Figure 5.10 shows the grasshopper script produced for calculating the energy performance. The simulation timestep and occupancy schedule are exactly followed, similar to the adaptive thermal comfort performance evaluation from Table 5.8 (Occupancy details). The details of both typologies' geometry are followed by tables 5.3, 5.4 and 5.5. The weather file for each climate zone in New Zealand is collected from the EPW file depository (Ladybug Tools, 2024). It is available online in the Grasshopper plugin, as Figure 5.3 shows importing EPW. The optimisation of energy performance in Table 5.10 shows the connection between the energy loads to build typology features, occupancy schedule, climatic conditions, classroom size and number of occupants. The supplementary file (simulation outcomes) submitted with this dissertation consists of a detailed simulation graph for annual energy loads in six climate zones of New Zealand for OECD standards in four categories: heating, cooling, infiltration, and natural ventilation.

5.3.3 Ventilation and Carbon Dioxide Multi-criteria Optimisation (MCO) Metrics

Natural ventilation is categorised into two types of ventilation: single-sided ventilation and cross-ventilation. Single-sided ventilation heavily depends on airflow from one side of the building, i.e., air entering and leaving from the same entrance or different walls of the same building. In cross-ventilation, enabling airflow through a building by establishing pathways between opposing exterior walls facilitates what is commonly known as cross ventilation. Specifically, air is introduced through an aperture on the windward facade, traversing the interior space and exiting via an opening on the leeward side. As it progresses through the ventilated area, this movement of air results in the absorption of thermal energy and the accumulation of airborne contaminants (Bhatia, 2015; (Ladybug Tools, 2024). Ventilation plays a critical role in designing smooth operations in educational spaces, as adequate ventilation offers a clean environment and removes contaminated air (Arya et al., 2023). Moreover, studies during and after post-COVID-19 specifically stressed the natural ventilation efficacy for healthy IAQ, less pathogen risk and lowered carbon dioxide concentration. The ventilation rates are usually measured in litre per second per person (l/s/p) or air change per hour (ACH) (Arya et al., 2024).

Monitoring carbon dioxide percentage in parts per million (ppm) has been a subject of study for decades in the IAQ and TC research area. To measure the efficacy of ventilation in a building, it is advised to measure the CO2 percentage in ppm as a proxy. A high percentage of ppm in indoor environments is directly associated with a poor ventilation rate (Cavallini-Rodriguez et al., 2022). Outdoor CO2 is generally between 400 and 500 ppm and is kept constant in the simulation strategy (Avery et al., 2019). No or inadequate ventilation rate can significantly spike carbon dioxide concentration. Educational spaces, particularly in cold and temperate climates, often see elevated carbon dioxide in the winter season. This phenomenon is often accentuated during the winter months, where reduced air exchange rates due to diminished frequency in the manipulation of fenestration systems contribute to the accumulation of carbon dioxide concentration (Ma et al., 2020). The worldwide COVID-19 pandemic has greatly increased the focus on the significance of indoor air quality and TC. Studies have shown that carbon dioxide (CO2) levels are a key indicator of occupant well-being and a dependable proxy for evaluating the potential spread of the COVID-19 virus in enclosed spaces (ASHRAE, 2021; Bhagat et al., 2020; Blocken et al., 2021). Accurate prediction of CO2 concentrations in indoor environments requires considering various factors, such as indoor temperatures, relative humidity, air circulation patterns, and the number of occupants (ASHRAE 55, 2021). Hence, considering CO2 as the main indicator for spreading not only COVID-19 but other illnesses related to health implications, various organisations have declared significant standards to combat the contamination of viruses and illnesses in enclosed spaces with higher occupancy (Arya et al., 2024; Bhagat et al., 2020).

5.3.3.1 Ventilation and Carbon Dioxide Multi-criteria Optimisation (MCO) Result

An ideal CO2 concentration after the emergence of COVID-19 is within the range of 800 ppm to 1000 ppm for healthy IAQ. To achieve the ideal CO2 range, airflow is expected to be between 8 l/s/p and 10 l/s/p or 5 – 6 ACH (Health and Safety Executive, 2022; REHVA, 2020; World Health Organisation, 2021a). Hence, New Zealand did propose a new DQLS (V 2.0) on Feb 2022 to strengthen the previous DQLS (V 1.0), 2017, with significant enhancement in IAQ and TC standards for primary schools. For this study, the DQLS (V 2.0) for the CO2 concentration range is simulated at three different ranges in compliance with different ventilation rates: 1.) 800 ppm at 12 l/s/p & 6 ACH; 2.) 1200 ppm at 7.5 l/s/p & 3.5 ACH; 3.) 2000 ppm at 4 l/s/p & 2 ACH. In addition, international standards are simulated as per Table 5.7. The Avalon and Canterbury block classroom profile is kept similar to Tables 5.3,5.4, and 5.5, and the occupancy profile is followed by Table 5.8. The grasshopper script for value input to simulate the indoor CO2 concentration is referred to in Figures 5.11 and 5.12. Since

Windows functions play a critical role here, it was set to be conditioned during the wintertime for 10-minute intervals every 90-120 minutes. The optimisation of CO2 in Table 5.11 shows the connection between the built typology features, occupancy schedules, climatic conditions, classroom size and number of occupants for ventilation rates for all international and DQLS V(2.0) standards in six climate zones of New Zealand. The supplementary file (simulation outcomes) consists of a detailed simulation graph for annual CO2 concentration in six climate zones of New Zealand for DQLS V(2.0) and international standards as per individual ventilation standards, temperature, and occupancy.

5.3.4 Optimal Design Changes for Avalon and Canterbury Blocks

The optimal design solution of both Avalon and Canterbury blocks was addressed through multi-criteria optimisation to achieve optimal indoor air quality (IAQ) and thermal comfort (TC) standards in response to post-COVID-19 requirements. Three key modification strategies were implemented, each addressing specific performance aspects of the building designs.

5.3.4.1 Structural Volumetric Optimal Design Modifications

The ceiling height was increased by 0.8 meters (~ 1m) in both Avalon and Canterbury blocks, resulting in a total classroom height of 3.5 meters. This modification significantly enhanced air volume within the teaching spaces, facilitating better air circulation and dilution of airborne contaminants. The increased room volume directly contributed to reduced CO2 concentration levels during peak occupancy periods throughout the day, extending until ventilation thresholds were reached. This modification proved particularly beneficial in maintaining healthier IAQ metrics while allowing for reduced mechanical ventilation requirements.

5.3.4.2 Fenestration and Thermal Envelope Design Modification

To optimise the balance between natural lighting, thermal performance, and ventilation, interventions were implemented in the window arrangement and the thermal insulation of the building envelope. The Avalon and Canterbury designs experienced a vertical adjustment in window positioning by 0.3 meters. Additionally, the window-to-wall area ratio was standardised at 25% across all models, enhancing solar heat gain while ensuring adequate natural illuminance and daylight.

To address climatic requirements, the thermal insulation of the building envelope was enhanced. In Christchurch, the roof's thermal resistance (R-values) was increased by 3.3% (roof), the walls by 6.5%, and the floor by 4%. In Queenstown, which is characterised by more severe weather conditions, more significant improvements were necessary, with R-value increases of 7% for the roof, 9.35% for the walls, and 3.8% for the floor. These targeted enhancements to the building's thermal envelope substantially reduced heating and cooling demands and minimised undesirable heat transfer across both investigated climate zones.

Table 5.9: Parametric Simulation result (Adaptive Thermal Comfort and Daylight)

Avalon Block Adaptive Comfort Percentage																		
OECD	Thermal Comfort Percentage (TCP)						Heating Sensation Percentage (HSP)						Cooling Sensation Percentage (CSP)					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
DQLS (V2.0)	78 - 82	85 - 90	77 - 80	78-82	70 - 74	69 - 78	1 -3	0 - 1	0 - 0.6	0 -1	0 -1	1-3	15 - 18	9-14	19 - 22	17 - 22	24 - 30	19 - 27
ASHRAE 62.1	67-71	70-74	64 - 70	59-64	71 - 74	65 - 70	1 -5	0 -1	0-0.5	0-0.4	0-0.3	0-0.2	27 - 28	26 - 30	29 - 35	36-40	25 - 28	30 - 34
CIBSE	64-68	75 - 77	70-72	71 - 76	60 - 64	55 - 61	1 -4	1-3.5	0 - 0.6	0 - 0.4	0 - 0.2	0 - 0.6	31 - 32	22 - 24	27 - 29	23 - 28	36 - 40	38 - 45
EN-15251	65 - 69	77 - 80	67 - 70	65 - 73	62 - 65	60 - 66	0.8 - 3.5	0 - 0.6	0-0.5	0-0.2	0-0.7	0-0.2	30 - 31	19 - 22	30 - 31	27 - 34	34 - 38	33 - 41
BB 99 & 101	69 - 73	82-86	73 - 79	75 - 82	66 - 72	50 - 61	0-0.4	0-0.7	0-0.7	0-0.2	0-0.3	0-0.4	26 - 30	13 - 16	19 - 26	18 - 24	27 - 33	38 - 49
Optimal Avalon	82 - 85	91 - 94	81-87	86 - 92	77 - 84	77 - 81	0-0.3	0-0.8	0-0.9	0-0.5	0-1.2	0-0.9	14 - 17	6 - 9	12 - 19	8 - 14	16 - 22	18 - 22
Canterbury Block Adaptive Comfort Percentage																		
OECD	Thermal Comfort Percentage (TCP)						Heating Sensation Percentage (HSP)						Cooling Sensation Percentage (CSP)					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN

DQLS (V2.0)	77-82	82-87	61 - 70	75 - 80	76 - 85	67 - 75	0-1.15	0-0.6	0-2.6	0.1-1.1	0-3.2	0-4.8	17 - 21	12 - 17	29 - 38	20 - 24	13 - 23	17 - 32
ASHRAE 62.1	77 - 82	73 - 81	62 - 70	73 - 77	61 - 68	69 - 75	0 – 0.5	0 – 2.2	0 – 3.7	0 – 0.4	0 – 3.1	0 - 4	17 - 23	17 - 26	28 - 37	22 - 27	30 - 38	22 - 29
CIBSE	79 - 84	83 - 87	72 - 78	77 - 82	70 - 77	53 - 65	0 – 0.6	0 – 3.1	0 – 4.1	0 – 0.4	0 – 4.2	0 – 3.5	16 - 21	11 - 17	19 - 27	17 - 21	21 - 29	33 - 46
EN-15251	83 - 87	80 - 86	60 - 73	64 - 75	56 - 68	39 - 58	0 – 0.5	0 – 1.1	0 – 3.4	0 – 0.4	0 – 2.1	0 – 3.1	13 - 17	13 - 18	24 - 39	25 - 35	30 - 44	39 - 60
BB 99 & 101	84 - 88	86 - 93	69 - 80	80 - 89	64 - 74	46 - 65	0 – 0.6	0 – 4.2	0 – 4.1	0 – 0.4	0 – 0.4	0 – 3.8	11 - 15	5 – 13	16 - 30	11 - 19	25 - 35	32 - 53
Optimal Canterbury	82 – 87	93 - 98	78 - 85	87 - 93	89 - 95	86 - 89	0 - 3	0-0.5	0 - 3.3	0-2.39	0-1.6	0-1.6	11-17	1.6-5.5	12 - 21	5 - 13	4 - 7	10 - 14

Avalon and Canterbury Block Daylighting percentage (DQLS (V2.0)												
	Daylighting Autonomy (DA)						Useful Daylight Illuminance (UDI)					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	49 - 88	50 - 88	45 - 87	50 - 88	48 - 86	49 - 85	71- 88	72 - 88	64 - 88	70 - 88	67 - 87	68 - 86
Optimal Avalon	50 - 88	51 - 88	47 - 87	51 - 88	50 - 87	50 - 86	73 - 89	72 - 89	66 - 88	71 - 88	69 - 87	69 - 86
Canterbury	51 - 88	52 - 88	48 - 87	47 - 88	42 - 86	40 - 85	69 - 88	69 - 89	67 - 88	69 - 88	62 - 87	66 -86

Optimal Canterbury	53 - 88	52 - 88	47 - 87	49 - 88	48 - 87	47 - 85	75 - 88	75 - 89	68 - 88	70 - 88	68 - 87	68 - 86

Table 5.10: Simulation Result (Energy Analysis)

Avalon Energy Analysis												
OECD	Heating Load (kWh/m^2)						Cooling Load (kWh/m^2)					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
DQLS V2.0	69	69	70	65	77	81.6	33	36	26	28	25	21
ASHRAE 62.1	54	52	52	53	62	65	12.5	11	9	11	12	8
CIBSE	53	50	41	51	75	76	16	18	10	16	13	13
EN-15251	61	65	54	63	70	77	25	21	16	18	18	10
Bb 99 & 101	65	65	52	63	80	81	33	29	21	28	26	17
Optimal Avlon	63	65	52	61	67.5	68.5	26	25	13.5	25	17	14
Canterbury Energy Analysis												
OECD	Heating Load (kWh/m^2)						Cooling Load (kWh/m^2)					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
DQLS (V2.0)	60	59	68	61	74	75	23	23	16	22	21	14
ASHRAE 62.1	50	52	50	53	61	63	13.5	11	11	12	18	12
CIBSE	61	53	50	52	69	70	13	14	16	15	18	14
EN-15251	65	62	52	61	70	74	18	16	15	21	16	15

BB 99 & 101	61	60	65.5	61	76	80	21	18	16	23	25	13.5
Optimal Canterbury	52	51	50	53	61	62	21	22	16	21	16	9.5
Infiltration load Analysis												
Negative Infiltration Load (kWh/m^2)							Positive Infiltration Load (kWh/m^2)					
DQLS V2.0	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	-3.6	-4.6	-3.6	-4.5	-5.1	-5	0.4	0.5	0.09	0.3	0.6	0.5
Optimal Avalon	-3	-4	-3.1	-4	-4.4	-4.4	0.2	0.1	0.1	0.2	0.4	0.4
Canterbury	-3.6	-3.6	-3.9	-4	-4.5	-4.4	0.4	0.09	0.2	0.2	0.5	0.4
Optimal Canterbury	-3.1	-3.1	-3.1	-3.6	-4	-3.9	0.1	0.1	0.2	0.09	0.2	0.2

Table 5.11: Simulation Result (Carbon Dioxide Concentration)

	CARBON DIOXIDE & VENTILATION (DQLS (V2.0)																	
	800 ppm @ 10l/s/p						1200 ppm @ 7l/s/p						2000 ppm @ 3l/s/p					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	876	877	877	875	876	876	1330	1349	1334	1347	1332	1334	2226	2211	2227	2246	2223	2249
Optimal Avalon	833	835	829	833	835	835	1255	1259	1246	1255	1260	1260	2090	2106	2071	2091	2106	2108
Canterbury	830	833	825	830	831	830	1254	1257	1236	1252	1254	1250	2096	2102	2052	2088	2099	2086
Optimal Canterbury	826	827	822	826	827	826	1243	1247	1233	1243	1247	1243	2071	2085	2047	2071	2084	2072

ASHRAE 62.1 CARBON DIOXIDE & VENTILATION												
	1000 ppm @ 6.4l/s/p						1000 ppm @ 7.5l/s/p					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	1211	1110	1070	1107	1075	1109	1101	1096	1061	1096	1061	1097
Canterbury	1072	1072	1068	1069	1069	1067	1062	1062	1060	1060	1060	1060
	CIBSE CARBON DIOXIDE & VENTILATION											
	800 ppm @ 12l/s/p						1000 ppm @ 12l/s/p					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	833	843	833	863	840	843	1034	1044	1034	1064	1034	1043
Canterbury	828	827	828	841	828	831	1028	1028	1028	1042	1027	1031
	EN-15251 CARBON DIOXIDE & VENTILATION											
	800 ppm @ 8l/s/p						1400 @ 8l/s/p					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	853	876	851	869	853	879	1453	1478	1411	1469	1453	1479

Canterbury	851	853	831	847	853	852	1451	1453	1431	1447	1453	1453
	BB 99&101 Carbon Dioxide and VENTILATION											
	1500 ppm @ 10 l/s/p						1500 ppm @ 8l/s/p					
	AKL	HAM	WELL	ROTO	CHCH	QTN	AKL	HAM	WELL	ROTO	CHCH	QTN
Avalon	1575	1577	1548	1575	1577	1580	1594	1601	1556	1590	1600	1601
Canterbury	1551	1554	1537	1535	1551	1551	1563	1568	1543	1551	1562	1562

5.3.4.3 Ventilation Control Strategy and Occupants' Clothing Value Modification

A manual ventilation protocol was established to maintain optimal CO2 levels while minimising energy losses. In the Avalon model, manual window opening was scheduled at 2-hour and 12-minute intervals during full occupancy. The Canterbury model implemented a more frequent intervention schedule with 90-minute intervals for 12-minute durations. This timestep for ventilation protocols achieved the dual objectives of maintaining CO2 concentrations close to the baseline ppm threshold while minimising thermal energy losses.

Occupant comfort parameters were adjusted to reflect regional climate realities, with clothing insulation (clo) values for Wellington, Christchurch and Queenstown modified from 0.75 to 0.80. This adjustment acknowledged the colder climate conditions in these regions and aligned thermal comfort expectations with typical occupant adaptations, resulting in comfort assessments and reduced heating demands without compromising perceived comfort.

The detailed explanation for multi-criteria optimisation results for each section (5.3.1.1, 5.3.2.1 & 5.3.3.1) is presented in section 5.4, discussion. The aim of the study from section 1 (Introduction), optimal design for IAQ and TC best practices in post – Covid 19 for six climate zones of New Zealand, is also described in section 5.4 below.

5.4 Discussion

5.4.1 Adaptive Thermal Comfort and Daylight

The multi-criteria optimisation of adaptive thermal comfort for both classroom typologies Avalon and Canterbury for DQLS (V2.0) presents meaningful insights. It is discussed against OECD standards and optimal design findings in sections 5.4.1.1, 5.4.1.2 and 5.4.2.

5.4.1.1 Avalon Block Adaptive Thermal Comfort Analysis

Table 5.9 contains the results discussed below for Avalon Thermal Comfort Analysis.

In Auckland, while the application of DQLS V2.0 resulted in a Total Comfort Percentage (TCP) ranging from 78% to 82%, which exceeded the performance of ASHRAE 62.1 (67-71%), CIBSE (64-68%), EN-15251 (65-69%) and BB 99&101 (69 -73%), the optimal solution enhanced this metric to 82-85%, making a 3-4 percentage point improvement. The Heating Season Comfort Percentage (HSP) remained consistently low at 1-3% across all OECD standards, with the optimal solution metric reducing cold discomfort to 0-0.3%. The Cooling Season Comfort Percentage (CSP) was moderate at 15-18%, significantly lower than ASHRAE 62.1 (27-28%) and other OECD standards, indicating a reduced overheating in the region's temperate climatic conditions. Hamilton demonstrated the highest TCP among all analysed regions under DQLS V2.0, achieving 85-90% exceeding other OECD standards. The optimal solution approached near-ideal thermal conditions, with a TCP of 91-94%. HSP was minimal at 0-1% for DQLS V2.0 and 0-0.8% for the optimal solution, signifying robust prevention of cold stress. Additionally, a substantial reduction in CSP was observed, from 9-14% (DQLS V2.0) to 6-9% (optimal solution), highlighting Hamilton's favourable conditions for minimising cooling loads. In Wellington, DQLS V2.0 achieved a competent TCP of 77-80%, similar to BB 99 & 101, and the optimal solution was 81-87%. HSP remained minimal at 0-0.6% (DQLS V2.0) and 0-0.9% (optimal solution). Notably, the optimal solution substantially improved CSP from 19-22% to 12-19%, representing a 7-percentage point improvement and highlighting the benefits of targeted interventions in this location. Rotorua presented TCP performance comparable to Auckland under DQLS V2.0, achieving 78-82% close with BB 99&101, exceeding other OECD standards. The optimal solution yielded good improvement after Hamilton, reaching 86-92% (TCP). Minimal HSP was observed at 0-1% (DQLS V2.0) and 0-0.5% (optimal solution). A 10 per cent drop in CSP was achieved, from 17-22% to 8-

14%, indicating the effectiveness of optimal strategies in mitigating overheating. Christchurch showed moderate baseline TCP performance under DQLS V2.0, achieving 70-74% close with ASHRAE 62.1 and slightly better than other OECD standards. Optimal solution led to TCP reaching 77-84%. HSP remained low at 0-1% (DQLS V2.0) and 0-1.2% (optimal solution), signifying effective prevention of cold conditions. A significant drop in CSP, from 24-30% to 16-22%, highlighting the efficacy of increased thermal insulation and Clo in balancing thermal performance. Despite challenging climatic conditions in Queenstown, DQLS V2.0 performed slightly better than ASHRAE 62.1 (65-70%) and outperformed other OECD standards, achieving a TCP of 69-78%. The optimal solution enhanced TCP to 77-81%. HSP was marginally higher than other OECD standards at 1-3% (DQLS V2.0). The reduction in CSP was reasonable, from 19-27% to 18-22%, yet the increased insulation and Clo value demonstrated its effectiveness in balancing heating and cooling needs. The Figures (5.25, 5.26 and 5.27) below shows the reference Avalon thermal chart for WELLINGTON DQLS v2.0 (TCP, HSP and CSP).

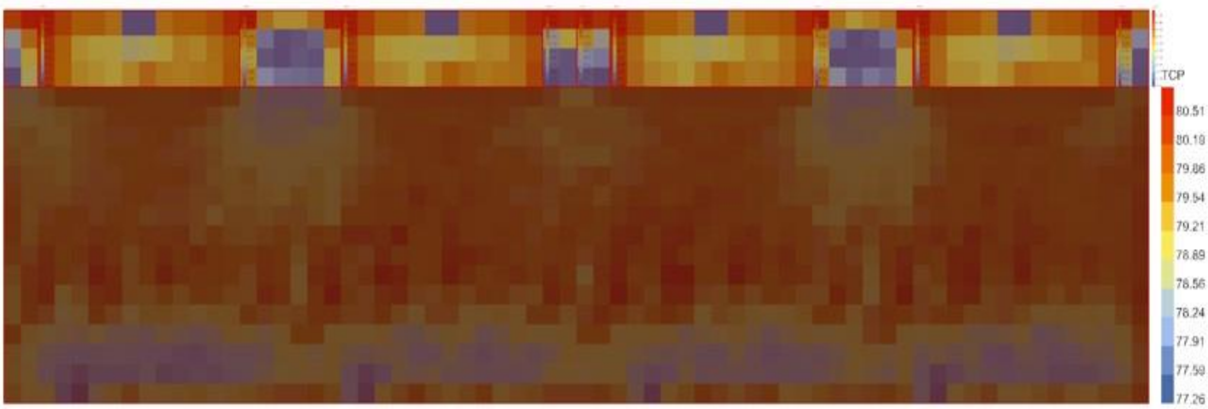

Figure 5.25: Avalon Wellington TCP

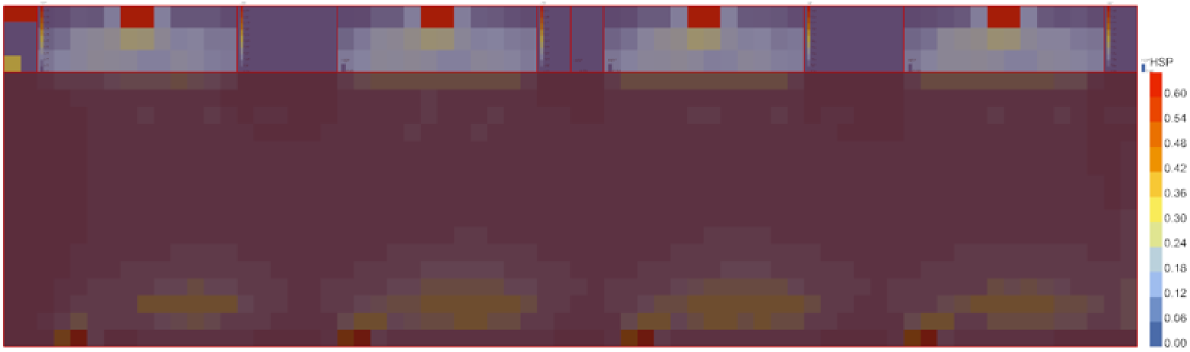

Figure 5.26 : Avalon Wellington HSP

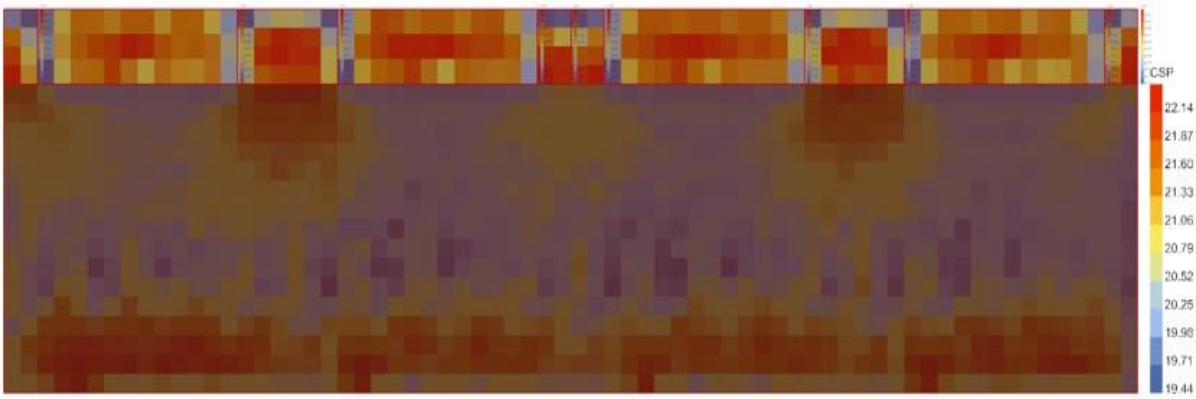

Figure 5.27 : Avalon Wellington CSP

5.4.1.2 Canterbury Block Adaptive Thermal Comfort Analysis

Table 5.9 contains the results discussed below for Canterbury Thermal Comfort Analysis

In Auckland, DQLS V2.0 obtained a Total Comfort Percentage (TCP) within the range of 77-82%, showing a marginal advantage to ASHRAE 62.1 (77-82%) and equivalence to CIBSE (79-84%). However, EN-15251 & BB 99&101 (83-87%) exceeds DQLS V2.0. The optimal solution in the Canterbury block resulted in a 5-percent improvement, reaching 82-87%. Heating Season Comfort Percentage (HSP) remained consistently low at 0-1.15% with other OECD standards, while the optimal solution led to an increase to 0-3%, still within acceptable limits. Cooling Season Comfort Percentage (CSP) was moderately reduced under

DQLS V2.0 (17-21%) compared to ASHRAE 62.1 (17-23%) while CIBSE performed equally, EN-15251 and BB 99 & 101 performed better (11-17%). The optimal solution enhanced CSP to 11-17%, meeting with OECD standards, indicating significant enhancement despite the region's moderate climate. Hamilton demonstrated significant TCP performance under DQLS V2.0 (82-87%), surpassing ASHRAE 62.1 (73-81%) and closely set with Other OECD standards (83-90%). The optimal solution achieved near-perfect thermal conditions, with a TCP of 93-98%. HSP was minimal at 0-0.6% (DQLS V2.0) to OECD standards and 0-0.5% (optimal solution). CSP was significantly lower than other standards under DQLS V2.0 (12-17%) except BB 99&101 (5-13%), and the optimal solution reduced CSP to 1.6-5.5%, demonstrating the improvement in cooling comfort. In Wellington, DQLS V2.0 demonstrated a lower TCP (61-70%), close with ASHRAE 62.1 (62-70%) and EN-15251 (60-73%), while CIBSE (72-78%) and BB 99&101 (69-80%). However, the optimal solution increased TCP to 78-85%, representing a 15-17% increase. HSP was higher under DQLS V2.0 (0-2.6%) compared to OECD standards; changes with the optimal design resulted in a marginal increase to 0-3.3%, remaining within acceptable limits. CSP was significantly higher than the Avalon typology in the same region under DQLS V2.0 (29-38%), close with ASHRAE 62.1 & EN-15251, while CIBSE and BB 99&101 attained (16 -27). The optimal changes reduced CSP to 12-21%. Rotorua achieved TCP performance under DQLS V2.0 (75-80%), close to ASHRAE 62.1 (73-77%) and CIBSE (77-82%), while BB 99&101 attained (80-89%). The optimal solution yielded a 12-13 per cent improvement, reaching 87-93%. HSP remained low at 0.1-1.1% (DQLS V2.0), slightly higher with OECD standards, optimal design, slight increase to 0-2.39% remaining acceptable. CSP was moderately reduced compared to ASHRAE 62.1 (22-27%) under DQLS V2.0 (20-24%), still higher than other OECD standards. The optimal solution reduced CSP to 5-13%. Christchurch exhibited TCP for DQLS V2.0 (76-85%), often surpassing other OECD standards under (60 – 75%). The optimal solution added enhanced TCP to reach (85-90 %). HSP was higher in DQLS V2.0 (0-3.2%) with OECD standards and Avalon block. The optimal design improved HSP to 0-1.6%. CSP was significantly lower than OECD standards under DQLS V2.0 (13-23%), and the optimal changes nearly eliminated cooling underline, reducing CSP to 4-7%, highlighting the effectiveness of increased thermal resistance with Clo. Despite challenging climatic conditions in Queenstown, DQLS V2.0 achieved TCP performance (67-80%) that surpassed ASHRAE 62.1 (69-75%) and other OECD standards. The optimal solution yielded a 19-percent improvement, reaching 86-89%. HSP was higher in DQLS V2.0 (0-4.8%), and the optimal design significantly reduced HSP to 0-1.6%. CSP was moderately reduced compared to ASHRAE 62.1 (22-29%) under DQLS V2.0 (17-32%) but higher than Avalon comparison, and the optimal solution reduced CSP to 10-14%, demonstrating the effective balance of heating and cooling requirements through increased thermal resistance and Clo value changed. Figures (5.28, 5.29 and 5.30) below show the reference Canterbury block thermal chart for Wellington DQLS v2.0 (TCP, HSP and CSP).

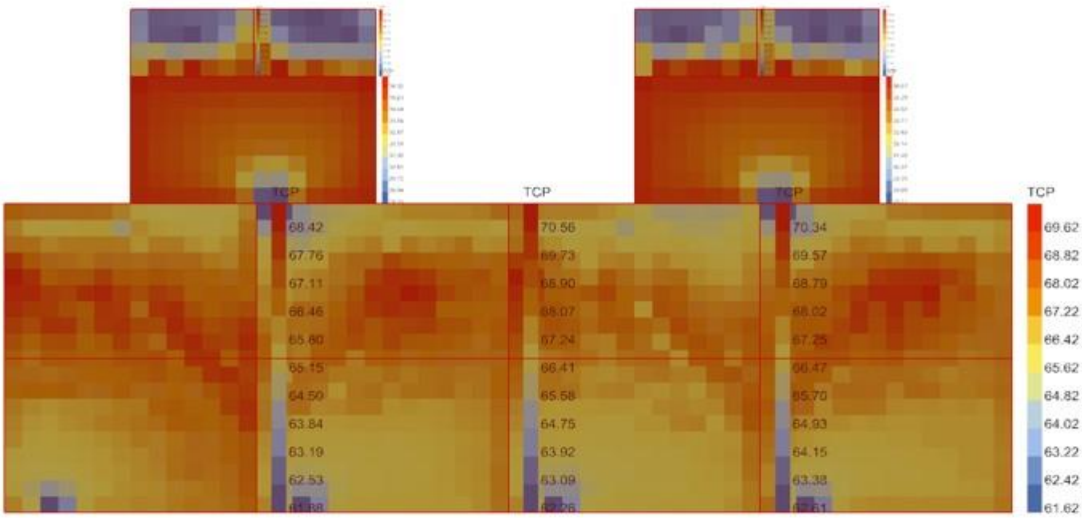

Figure 5.28 : Canterbury Wellington TCP

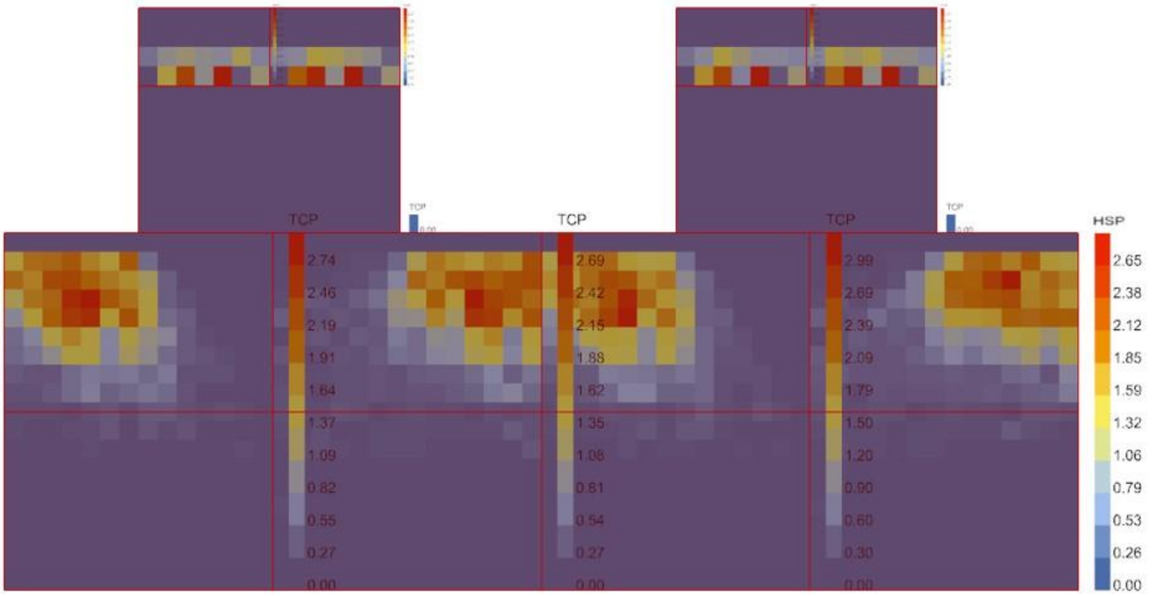

Figure 5.29 : Canterbury Wellington HSP

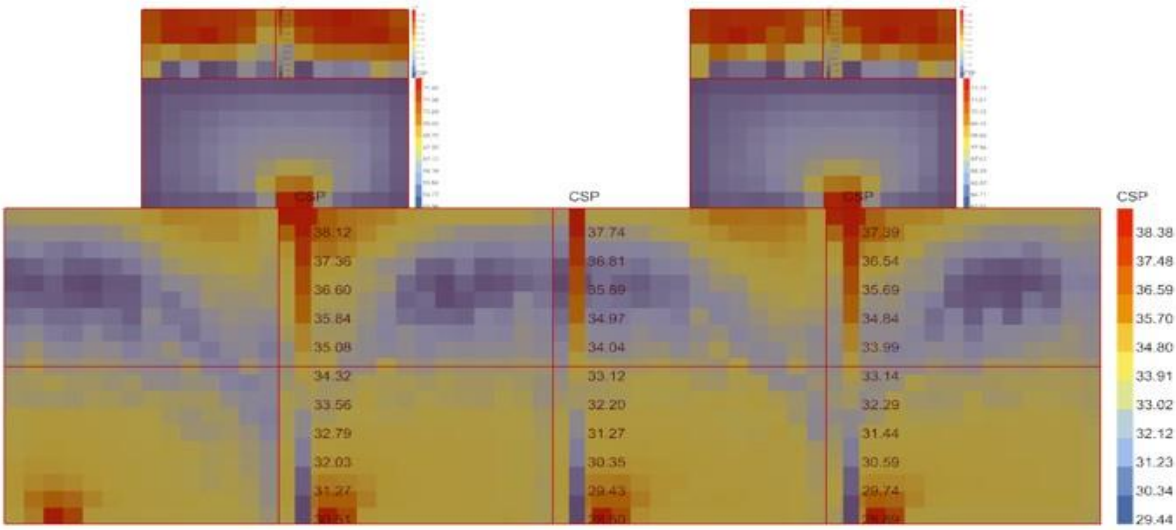

Figure 5.30 : Canterbury Wellington CSP

5.4.2 Avalon and Canterbury Blocks Daylight Analysis

Table 5.9 contains the results discussed below for Avalon and Canterbury Daylight and Illuminance Analysis.

The Avalon block showed that the lowest daylight (DA) value received in all six climate zones of New Zealand is between 47-50%, and the highest percentage received in all six climate zones of New Zealand is between 85-88%. Wellington exhibited the lowest point, receiving (47-87%), while Hamilton and Rotorua exhibited the highest, receiving 50-88%. The optimal solution showed marginal improvement, with the lowest point for Wellington improved from 47-87% to 45-87%. Additionally, Hamilton Rotorua improved from 51-88% to 50-88%, and Auckland, Christchurch and Queenstown achieved 49-87%. The Useful daylight illuminance (UDI) for the Avalon block received a minimum percentage of 66-89% for Wellington, and the maximum UDI value achieved for Hamilton and Auckland was 72-88%, and Rotorua was marked at 71-87%, and Christchurch and Queenstown achieved 69-86%. The optimal solution for the UDI value showed improvement with a 2% decrease for all six climate zones, while there was no change in Hamilton.

The Canterbury block showed the lowest daylight (DA) received in Wellington and Queenstown at 47- 86%, while Auckland and Hamilton exhibited 51-88%, and Rotorua and Christchurch received relatively equal with 47-88%. The optimal solution significantly improved with Christchurch from 47-86% to 42-87% and Queenstown from 48-85% to 44-85%. Meanwhile, Auckland and Rotorua improved by 2%, Wellington improved by 1%, and Hamilton remained the same. The UDI range in Canterbury exhibited a similar trend to the DA value in Canterbury. The lowest UDI achieved is by Christchurch and Queenstown at 68-87%, Auckland and Hamilton at 75-89%, and Rotorua shared similar UDI values between 69-89% to Wellington. The optimal solution showed significant improvement in all six climate zones, with the optimum result receiving Auckland, Hamilton, and Rotorua UDI per cent to 69-88%. While Wellington showed improvement by a 1% decrease, Christchurch improved by a 6% decrease and Queenstown by 2%.

5.4.3 Energy Analysis

5.4.3.1 Avalon Block Energy Analysis

Table 5.10 contains the results discussed below for Avalon Energy Analysis

A comparative analysis of heating load efficiency, referenced against OECD standards, reveals significant disparities across New Zealand's diverse climatic regions in Avalon Block. The DQLS V2.0 shows a relatively consistent pattern of high energy demand in the northern regions, with both Auckland and Hamilton recording 69 kWh/m² and in southern altitude peaking between 75-80 kWh/m2. In contrast, the ASHRAE standard 62.1 indicates a more moderate energy consumption profile, ranging from 52 kWh/m² in Hamilton & Wellington to 65 kWh/m² in Queenstown, thus demonstrating greater overall efficiency. The CIBSE standards exhibit significant geographical variability, with substantial energy use in Auckland at 53-50 kWh/m² lower than DQLS V2.0, compared to more efficient performance in Wellington at 41 kWh/m² and Christchurch with similar to DQLS V2.0 75 kWh/m2, respectively. The EN-15251 follows a similar trend to CIBSE, showing energy use in Auckland at 62 kWh/m² while achieving efficient operation in Wellington at 54 kWh/m², Christchurch & Queenstown between 70-77 kWh/m2, similar loads to CIBSE. Building Bulletins (BB) 99 & 101 consistently demonstrate the higher overall energy demands similar to DQLS V2.0, the northern region values between 63-65 kWh/m2, and the southern region at 81 kWh/m² in Christchurch and Queenstown in all OECD standards. The Optimal Avalon solution, in contrast, presents a more balanced energy utilisation profile across all climatic zones, with values ranging from 60 kWh/m² in the northern region to 67 kWh/m² in the southern region, reducing the demands by 6-16%. Figure 5.31 shows the heating load graph for the Avalon block (AKL - DQLS v2.0).

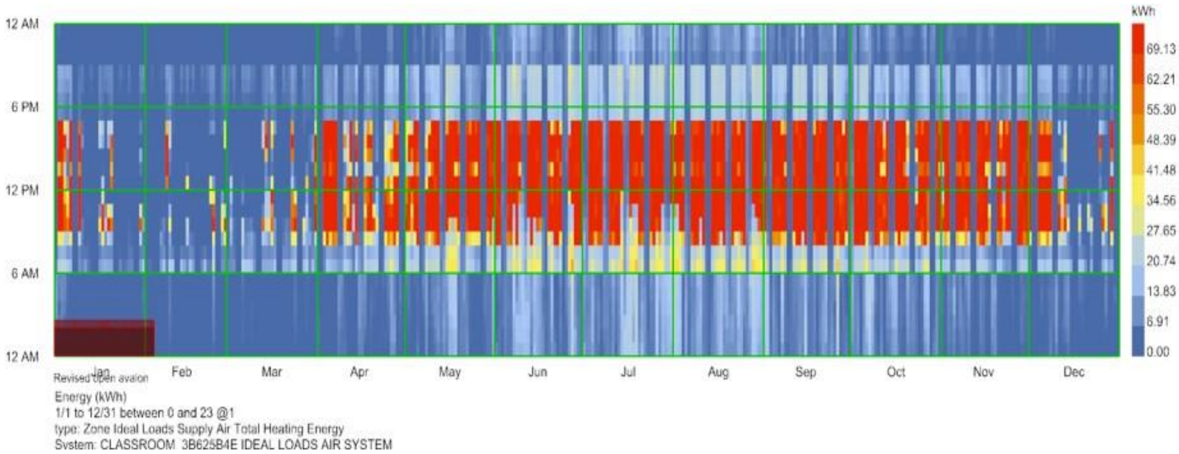

Figure 5.31 : Avalon Auckland Heating load

However, the cooling load performance across OECD standards highlights significant differences. The ASHRAE standard 62.1 consistently demonstrates reasonable cooling efficiency, ranging from 8-13 kWh/m² in Queenstown to Wellington and 12 kWh/m² in Auckland to 10 kWh/m2 in Rotorua. In contrast, the DQLS V2.0 shows cooling performance between 21-36 kWh/m2, particularly lowest at 21 kWh/m² in Queenstown and highest with Auckland at 35 kWh/m². The CIBSE standards indicate favourable performance across most regions, with particularly efficient outcomes between 10-18 kWh/m2, with the lowest in Wellington at 10 kWh/m² and Queenstown at 13 kWh/m², though with variations across different locations, highest at 18 kWh/m2 in Hamilton. The EN-15251 maintains a reasonable efficacy, with the lowest load in Queenstown at 10 kWh/m² & highest in Auckland (25 kWh/m2). Building Bulletins (BB) 99 & 101 demonstrate a wide range of performance, from highly effective cooling in Queenstown at 17 kWh/m² to significantly inefficient operation in Auckland, Hamilton and Christchurch between 26-33 kWh/m², quite similar to DQLS V2.0.

The Optimal Avalon solution presents a mixed profile, with outstanding performance in Wellington at 13 kWh/m² and Queenstown at 14 kWh/m2. But high values in Auckland & Hamilton at 25 kWh/m². This suggests that the Optimal Avalon solution involves design compromises that prioritise performance in specific climatic regions over others. The optimal solution delivered moderate results in the northern regions for Cooling by 10-21%, but in the southern region, the cooling load was reduced by 35% in southern regions. Figure 5.32 shows the cooling load graph for the Avalon block (AKL - DQLS v2.0).

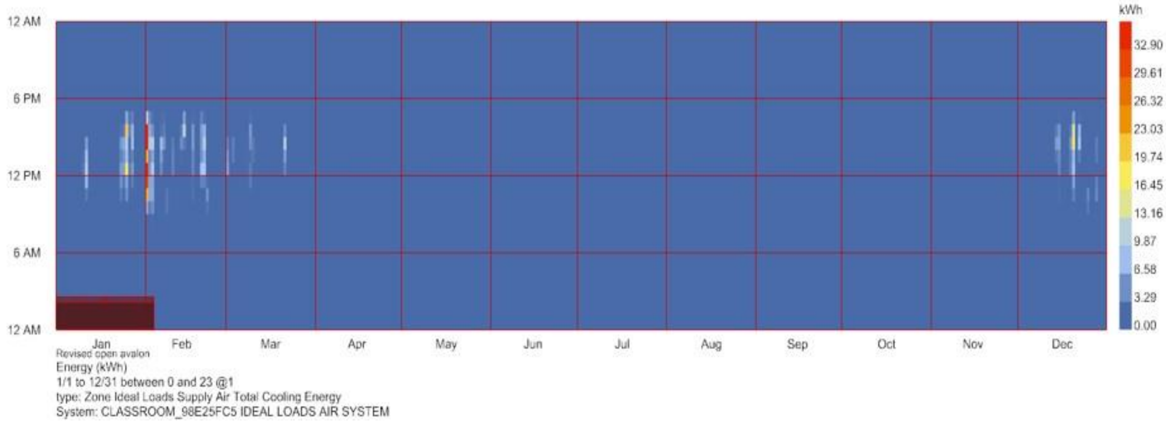

Figure 5.32 : Avalon Auckland Cooling load

The infiltration energy loads exhibit substantial meaning in six climate zones of New Zealand. The higher negative value in the southern region directly correlates with high heating loads in the same region. While a lower value in the northern region directly correlates with a high cooling load in the northern region. Avalon block exhibits negative values from -3.6 to -5.1 kWh/m2 (Auckland to Queenstown). The optimal solution improved by 10 -15% across all six climate zones. Figure 5.33 shows the infiltration load graph for the Avalon block (AKL)

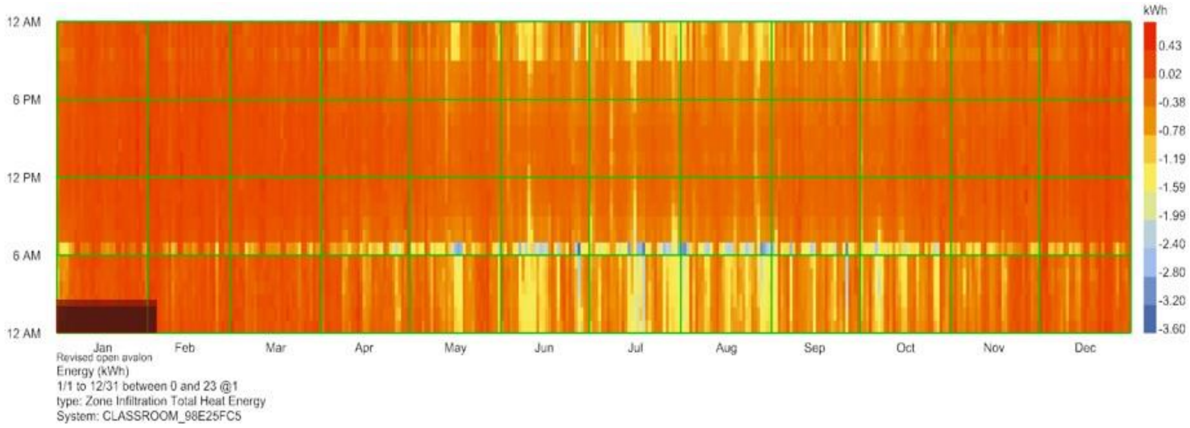

Figure 5.33 : Avalon Auckland Infiltration load

5.4.3.2 Canterbury Block Energy Analysis

Table 5.10 contains the results discussed below for Canterbury Energy Analysis.

The Canterbury Block analysis of heating load efficiency, using international standards (OECD), uncovers significant regional variations across New Zealand. The DQLS V2.0 shows moderate energy demands in Auckland (60 kWh/m²) and Hamilton (59 kWh/m²), with an increase in Wellington (68 kWh/m²) and a more rise in Christchurch (74 kWh/m²) and Queenstown (75 kWh/m²). The ASHRAE 62.1 demonstrates lower overall energy consumption, ranging from 50-52 kWh/m² in Auckland and Hamilton to 63 kWh/m² in Queenstown, indicating improved heating efficiency across diverse climatic zones. The CIBSE standards reveal geographical variability of higher heating loads in the northern regions, with Auckland at 61 kWh/m² compared to significantly lower requirements in Wellington (50 kWh/m²) and high with Christchurch (69 kWh/m²) & Queenstown (70 kWh/m2). The EN-15251 follows a similar trend, showing substantial energy use in Auckland (65 kWh/m²) and Hamilton (62 kWh/m²) while recording lower values in Wellington (52 kWh/m²), slight increases in the southern regions to 70 kWh/m2. Building Bulletins (BB) 99 & 101 consistently demonstrate similar energy demands to DQLS V2.0, particularly in Auckland & Rotorua (61 kWh/m²) and Christchurch (76 kWh/m²), the lowest with Hamilton (60 kWh/m2). In contrast, the Optimal Canterbury solution presents a balanced energy utilisation profile across all climatic zones, with values ranging from 50 kWh/m² to 60 kWh/m², offering consistent performance while reducing the heating loads by 13-20 kWh/m2 in all climate zones relative to other evaluated standards. Figure 5.34 shows the heating load graph for the Canterbury block (QTN - DQLS v2.0).

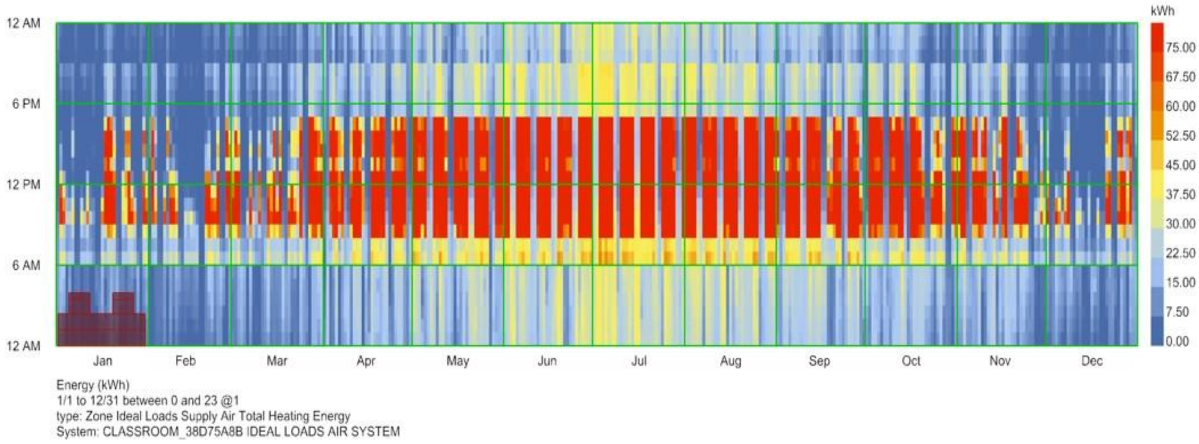

Figure 5.34 : Canterbury Queenstown Heating load

The analysis of cooling load effectiveness across various OECD standards reveals a diverse range of performance within the Canterbury block. The DQLS, V2.0, shows a variable trend in cooling demands, beginning with moderate requirements in Auckland at 23 kWh/m²; cooling energy expenditure decreases progressively southward to 16 kWh/m² in Wellington and 14 kWh/m² in Queenstown, rising again in Christchurch to 21 kWh/m². In contrast, ASHRAE 62.1 exhibits a more uniform distribution of cooling loads, ranging between 11-18 kWh/m² in Auckland, Hamilton, and Rotorua, around 13 kWh/m2, while highest in Christchurch with 18 kWh/m2, respectively. The CIBSE standards present a relatively consistent cooling performance across the assessed regions between 13 to 18 kWh/m2, with 13 kWh/m² in Auckland to 15 kWh/m² in (Hamilton & Rotorua), Christchurch & Queenstown very similar to ASHRAE 62.1 at 18 kWh/m2 & 12 kWh/m². The EN-15251 indicates higher cooling loads in the northern cities, specifically 18 kWh/m² in Auckland and 16 kWh/m² in Hamilton, while showing moderate efficiency in Wellington at 15 kWh/m² and increased energy use in the Rotorua with 21 kWh/m2, in Christchurch and Queenstown below 20 kWh/m2. Building Bulletins (BB) 99 & 101 demonstrate a stable pattern of cooling demands in the northern region, ranging from 21 -23 kWh/m² (AKL, HAM & ROTO), while (WELL& CHCH) nearly equal to 15 kWh/m2 and Queenstown at 10 kWh/m2. The Optimal Canterbury solution, in contrast, achieves less reduced cooling loads in the northern region by 8 % and the southern region by 20 %. Figure 5.35 shows the cooling load graph for the Canterbury block (QTN - DQLS v2.0).

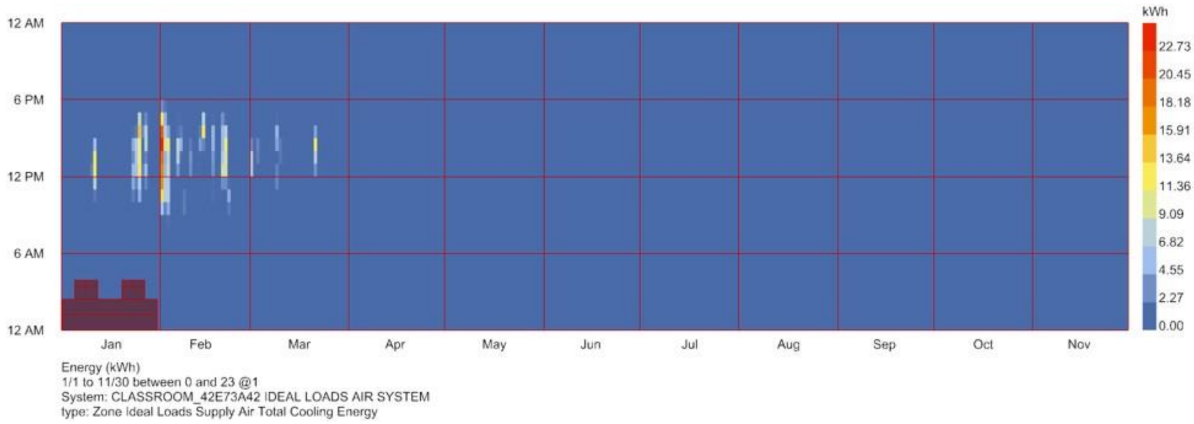

Figure 5.35 : Canterbury Queenstown Cooling load

The infiltration energy loads exhibit substantial meaning in six climate zones of New Zealand. The higher negative value in the southern region directly correlates with high heating loads in the same region. While a lower value in the northern region directly correlates with a high cooling load in the northern region. Canterbury block exhibits negative values from -3.6 to – 4.5 kWh/m2 (Auckland to Queenstown). The optimal solution improved by 10 -12% across all six climate zones. Figure 5.36 shows the infiltration load graph for the Canterbury block (QTN - DQLS v2.0)

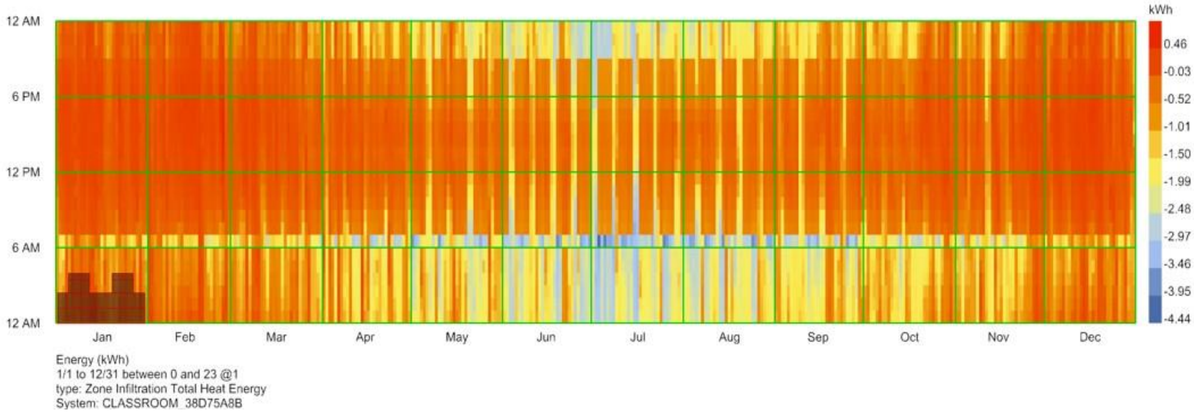

Figure 5.36 : Canterbury Queenstown Infiltration load

5.4.4 Carbon Dioxide and Ventilation Analysis

5.4.4.1 Avalon Block Carbon Dioxide and Ventilation Analysis

Table 5.11 contains the results discussed below for Avalon Carbon dioxide Analysis.

In Auckland, the DQLS V2.0 showed a spike in CO2 concentration between 9 to 11%, the baseline of three distinctive values: 800 ppm (12 l/s/p), 1200 ppm (7.5 l/s/p) and 2000 ppm (4 l/s/p). ASHRAE 62.1 showed a spike between 10 and 21% at 1000 ppm for 6.4 l/s/p and 7.4 l/s/p, while CIBSE exhibited a 4.1 % spike with 800 ppm baseline value against 12 l/s/p followed by 3.4% spike for 1000 ppm against 12 l/s/p. EN-15251 was simulated at two distinctive baseline values, 800 ppm at 8 l/s/p and 1400 ppm at 8 l/s/p, resulting in a 6.5% and 3.8% increase. Moreover, BB 99& 101 were simulated at 1500 ppm at two distinct ventilation rates: 10 l/s/p attained 5 %, and 8 l/s/p attained a 6.2% spike in concentration. In Hamilton, DQLS V2.0 measurements indicated an elevation of CO_2 levels, between 8-10% above target values at 800 ppm (12 l/s/p), 1200 ppm (7.5 l/s/p), and 2000 ppm (4 l/s/p). ASHRAE 62.1 showed a 12-19% increase at 1000 ppm at 6.4 l/s/p and 7.5 l/s/p ventilation rates. CIBSE guidelines transmitted a 3.7% increase at 800 ppm (12 l/s/p) and a 3.9% increase at 1000 ppm (12 l/s/p). EN-15251 simulations achieved a 7.8% increase at 800 ppm (8 l/s/p) and a 4.1% increase at 1400 ppm (8 l/s/p). BB 99&101 simulations at 1500 ppm showed a 4.8% increase at 10 l/s/p and a 4.6% increase at 8 l/s/p. DQLS V2.0 demonstrated a 7-11% increase in CO_2 concentrations across the three baseline measurements in Wellington. ASHRAE 62.1 exhibited a 13-17% increase at 1000 ppm with both ventilation rates. CIBSE parameters showed a 3.7% increase at 800 ppm and a 3.4% increase at 1000 ppm. EN-15251 simulations revealed a 6.4% increase at 800 ppm and a 4.4% increase at 1400 ppm. BB 99&101 simulations indicated a 5.6% increase at 10 l/s/p and a 5.1% increase at 8 l/s/p. In Rotorua, DQLS V2.0 measurements showed CO_2 concentration increases of 9-11% across the baseline values. ASHRAE 62.1 displayed 11-19% increases at 1000 ppm. CIBSE parameters resulted in a 5.1% increase at 800 ppm and a 4.7% increase at 1000 ppm. EN-15251 simulations showed a 7.2% increase at 800 ppm and a 5.1% increase at 1400 ppm. BB 99&101 measurements indicated a 5.5% increase at 10 l/s/p and a 5.4% increase at 8 l/s/p. In Christchurch, DQLS V2.0 findings revealed CO_2 concentration increases of 8-10% across the three baseline values. ASHRAE 62.1 showed 10-14% increases at 1000 ppm with both ventilation rates. CIBSE parameters resulted in a 3.8% increase at 800 ppm and a 3.5% increase at 1000 ppm. EN-15251 simulations showed a 6.4% increase at 800 ppm and a 4.1% increase at 1400 ppm. BB 99&101 measurements indicated a 5.2% increase at 10 l/s/p and a 5.6% increase at 8 l/s/p. Similarly, DQLS V2.0 showed CO_2 concentration increases of 9-11% across the baseline values in Queenstown. ASHRAE 62.1 exhibited 11-15% increases at 1000 ppm. CIBSE parameters resulted in a 3.5% increase at 800 ppm and a 3.8% increase at 1000 ppm. EN-15251 simulations showed a 7.3% increase at 800 ppm and a 4.3% increase at 1400 ppm. BB 99&101 measurements indicated a 5.9% increase at 10 l/s/p and a 6.4% increase at 8 l/s/p. The Optimal solution in Avalon Block improved by 4 % to 5.5%, meeting all OECD standards, ranging from 4% to 7% across all climate zones above the baseline value. Figures 5.37 and 5.38 show the carbon dioxide concentration for Avalon Block (CHCH at 800ppm and 2000 ppm)

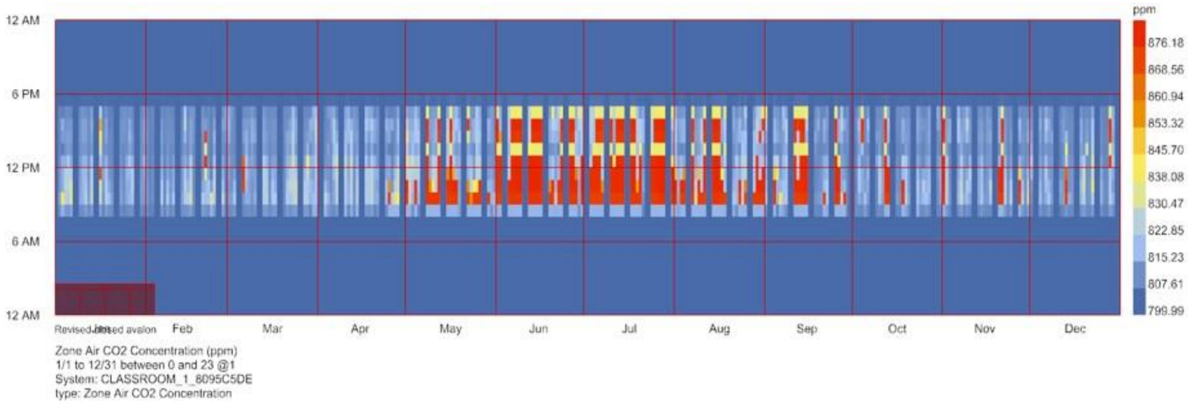

Figure 5.37 : Avalon Christchurch CO2 @ 800 ppm

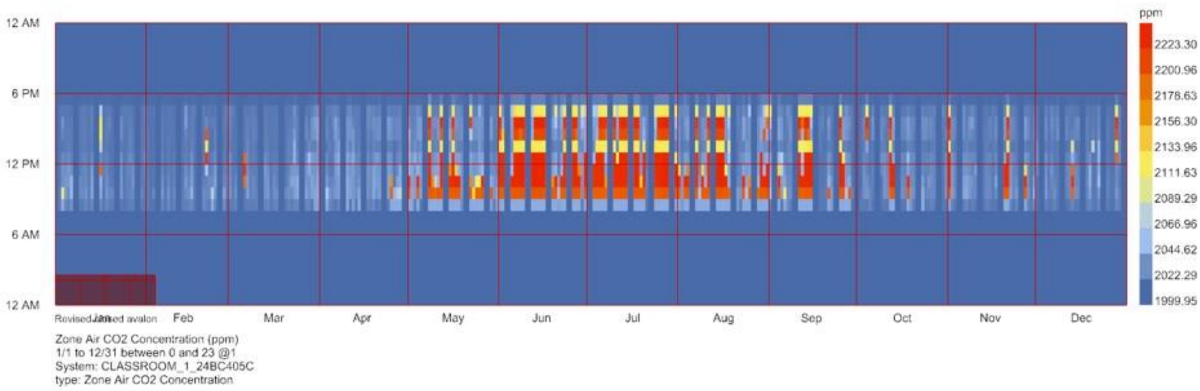

Figure 5.38 : Avalon Christchurch CO2 @ 2000 ppm

5.4.4.2 Canterbury Block Carbon Dioxide and Ventilation Analysis

Table 5.11 contains the results discussed below for Canterbury Carbon dioxide Analysis.

In Auckland, DQLS V2.0 exhibited a CO_2 concentration increase ranging from 3.8% to 4.8% across three distinct baseline values: 800 ppm (12 l/s/p), 1200 ppm (7.5 l/s/p), and 2000 ppm (4 l/s/p). ASHRAE 62.1 showed a 7.2% increase at 1000 ppm for 6.4 l/s/p and a 6.2% increase for 7.5 l/s/p. CIBSE demonstrated a 3.5% increase at 800 ppm (12 l/s/p) and a 2.8% increase at 1000 ppm (12 l/s/p). EN-15251 simulations at 800 ppm (8 l/s/p) and 1400 ppm (8 l/s/p) resulted in a 6.4% and 3.6% increase, respectively. BB 99&101 simulations at 1500 ppm showed a 3.4% increase at 10 l/s/p and a 4.2% increase at 8 l/s/p. In Hamilton, DQLS V2.0 showed a CO_2 concentration increase between 4.1% and 5.1% across the three baseline values. ASHRAE 62.1 exhibited a 7.2% increase at 1000 ppm for 6.4 l/s/p and a 6.2% increase for 7.5 l/s/p. CIBSE demonstrated a 3.4% increase at 800 ppm (12 l/s/p) and a 2.8% increase at 1000 ppm (12 l/s/p). EN-15251 simulations resulted in a 6.6% and 3.8% increase. BB 99&101 simulations at 1500 ppm showed a 3.6% increase at 10 l/s/p and a 4.5% increase at 8 l/s/p. In Wellington, DQLS V2.0 exhibited a CO_2 concentration increase between 3.1% and 4.7% across the three baseline values. ASHRAE 62.1 showed a 6.8% increase at 1000 ppm for 6.4 l/s/p and a 6.0% increase for 7.5 l/s/p. CIBSE demonstrated a 3.5% increase at 800 ppm (12 l/s/p) and a 2.8% increase at 1000 ppm (12 l/s/p). EN-15251 simulations resulted in a 3.9% and 2.2% increase. BB 99&101 simulations at 1500 ppm showed a 2.5% increase at 10 l/s/p and a 2.9% increase at 8 l/s/p. In Rotorua, DQLS V2.0 exhibited a CO_2 concentration increase between 3.8% and 4.4% across the three baseline values. ASHRAE 62.1 showed a 6.9% increase at 1000 ppm for 6.4 l/s/p and a 6.0% increase for 7.5 l/s/p. CIBSE demonstrated a 5.1% increase at 800 ppm (12 l/s/p) and a 4.2% increase at 1000 ppm (12 l/s/p). EN-15251 simulations resulted in a 5.9% and 3.4% increase. BB 99&101 simulations at 1500 ppm showed a 2.3% increase at 10 l/s/p and a 3.4% increase at 8 l/s/p. In Christchurch, DQLS V2.0 exhibited a CO_2 concentration increase between 3.9% and 5.0% across the three baseline values. ASHRAE 62.1 showed a 6.9% increase at 1000 ppm for 6.4 l/s/p and a 6.0% increase for 7.5 l/s/p. CIBSE demonstrated a 3.5% increase at 800 ppm (12 l/s/p) and a 2.7% increase at 1000 ppm (12 l/s/p). EN-15251 simulations resulted in a 6.6% and 3.8% increase. BB 99&101 simulations at 1500 ppm showed a 3.4% increase at 10 l/s/p and a 4.1% increase at 8 l/s/p. In Queenstown, DQLS V2.0 exhibited a CO_2 concentration increase between 3.8% and 4.3% across the three baseline values. ASHRAE 62.1 showed a 6.7% increase at 1000 ppm for 6.4 l/s/p and a 6.0% increase for 7.5 l/s/p. CIBSE demonstrated a 3.9% increase at 800 ppm (12 l/s/p) and a 3.1% increase at 1000 ppm (12 l/s/p). EN-15251 simulations resulted in a 6.5% and 3.8% increase. BB 99&101 simulations at 1500 ppm showed a 3.4% increase at 10 l/s/p and a 4.1% increase at 8 l/s/p. The Optimised solution in Canterbury Block improved by 3 % to 3.5%, surpassing all OECD standards, ranging from 0.5% to 1.5% across all climate zones. Figures 5.39 and 5.40 show the carbon dioxide concentration for Canterbury Block (CHCH at 800 ppm and 2000 ppm).

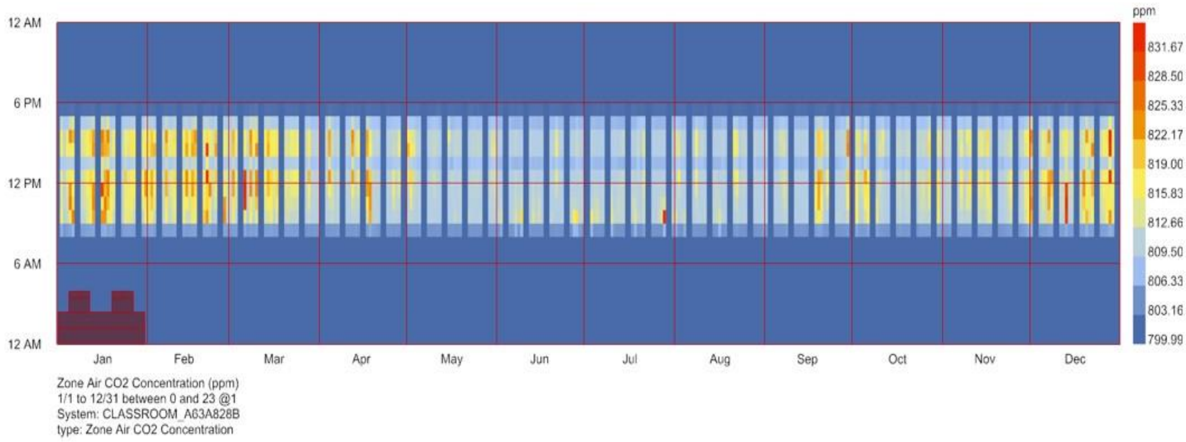

Figure 5.39 : Canterbury Christchurch @ 800 ppm

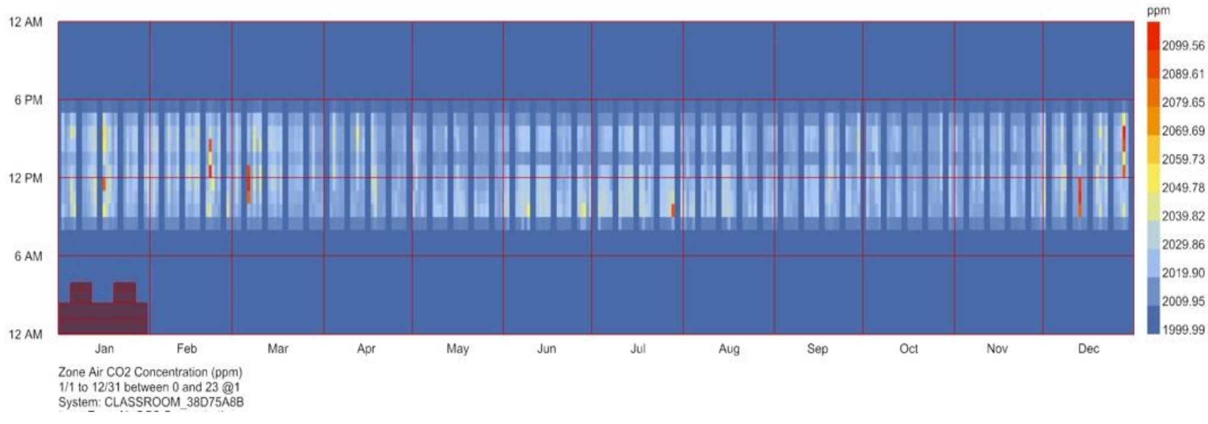

Figure 5.40 : Canterbury Christchurch @ 2000 ppm

5.4.5 Avalon and Canterbury Block Holistic Comparative Analysis

DQLS V 2.0 consistently outperforms the OECD standards in the Avalon block's adaptive thermal comfort (TCP) percentage with a remarkable mean value above 70%, even in diverse climatic conditions. Low (HSP) values indicate good thermal resistance for preventing cold stress during winter, and moderate (CSP) values indicate limited overheating compared to OECD standards. Christchurch and Queenstown did show the lowest TCP value but comparatively high HSP value, but Auckland and Christchurch had the highest CSP value. The optimal design changes enhanced the TCP value by adding a 3-10% and CSP value by 5-10%. Low HSP value is important for an educational environment where thermal comfort can impact cognitive performance. A low CSP value suggests good management with a rise in global temperature. In Canterbury, DQLS V2.0 did equally well in all climate zones against OECD standards for TCP values, meaning up to 70%, slightly lower than the Avalon block. High (HSP) values in Christchurch and Queenstown indicate moderately less effectiveness than Avalon Block in managing cold stress in winter seasons, and high CSP values in Auckland, Rotorua, and Christchurch indicate little concerning overheating problems concerning Avalon Block. High CSP values indicate a challenge in the summertime to manage heat gain. The optimal design interventions enhanced the TCP value by 5-17%, the HSP value improved by 20-25%, and the CSP value reduced by 18% in most climate zones.

Both Avalon and Canterbury typologies perform equally better with daylight and Useful illuminance. The mean DA for Avalon and Canterbury values above 47% and UDI above 67%. Consistent performance with 35% WWR in Avalon and 30% WWR in Canterbury. Both Avalon and Canterbury perform collectively resilient with context to diversified climatic conditions. The value for relatively small standard deviations in maximum values indicates reliable upper-performance thresholds. Areas with higher UDI often experience increased solar heat gain, leading to higher cooling demands (higher CSP) (Grynning et al., 2014). Conversely, reducing window area or using shading to decrease cooling loads can potentially reduce useful daylight (Kim et al., 2015; Lakhdari et al., 2021). Similarly, the Avalon and Canterbury blocks show high UDI and CSP values in Wellington, Christchurch and Queenstown. The optimal design changes for reducing the WWR to 25% improved the CSP values but also helped to strengthen the thermal comfort overall.

Comparing the energy performance across New Zealand's varied climate zones reveals distinct patterns in the Avalon and Canterbury building designs. The Optimal Avalon solution demonstrates a balanced heating performance (52-68.5 kWh/m²) across climate zones compared to standard implementations, particularly showing improvement over DQLS (V2.0), which requires 65-81.6 kWh/m² across north to south regions. The cooling demands were significantly reduced in northern and southern regions, ranging from 21-36 kWh/m2 to 14-25 kWh/m2, similar to other OECD standards. This improvement directly correlates with the increased ceiling height to 3.5m and vertical window placement of 0.3m, which enhances air stratification and reduces energy demands (Tong et al., 2020). Similarly, the Optimal Canterbury solution achieves more consistent heating performance (42-67 kWh/m²) than conventional standards, with notable improvements in Auckland and Hamilton, benefiting from the strategic vertical repositioning of windows by 0.3m and the reduced WWR of 25% (Elghamry & Hassan, 2020; Lakhdari et al., 2021). Cooling load analysis reveals significant regional variations, with the Optimal Avalon solution showing excellent performance in Wellington (3.83 kWh/m²) but higher values in Hamilton (33 kWh/m²). The Optimal Canterbury solution demonstrates more consistent cooling efficiency across regions, achieving remarkably low values in Wellington (1.2 kWh/m²) and Christchurch (6 kWh/m²). These improvements are directly attributable to the enhanced R-values implemented in the thermal envelope, particularly the increases of 3.3% for roofs, 6.5% for walls, and 4% for floors in Christchurch, and the more aggressive enhancements of 7% for roofs, 9.35% for walls, and 3.8% for floors in Queenstown (Su, 2017; Su et al., 2022). The infiltration load appears highly effective in DQLS V2.0 for both Avalon and Canterbury. The Avalon infiltration load for the northern region (AKL, HAM & ROTO) was between 0.3-0.5 kWh/m2, while the southern region (CHCH, WELL & QTN) was slightly higher between 0.5-0.6 kWh/m2. However, the infiltration value is close to 0, which indicates the marginal heat transfer to heat gain, while the negative infiltration value indicates heat losses (Liu et al., 2020).

Across all climate zones, Canterbury Block exhibits better CO2 performance by consistently demonstrating lower concentrations than Avalon Block, suggesting a bigger volume of classrooms and lower WWR% significantly improve IAQ by channelising the proper airflow (Hassieb et al., 2024). The Avalon block at 800 ppm base value presented a 9-10% spike at 10 l/s/p. Meanwhile, the Canterbury block at the same base value, 10 l/s/p, showed a spike of 5% Similarly, for 7 l/s/p at a base value of 1200 ppm, the Avalon resulted in a spike of 11% and Canterbury accounts for 4-4.5%; for 3 l/s/p at 2000 ppm, Avalon showed an 12% spike, and Canterbury showed 4.8-5% spike. With every 3-4 l/s/p decrease in airflow, the Avalon shows a spike of 2-3%; on the other hand, Canterbury showed 1-1.5%. The manual window timestep intervention adjustment is every 90 - 120 minutes in Avalon and Canterbury for 12 minutes (Korsavi et al., 2020; Stabile et al., 2017), along with an 0.8-metre ceiling height increase (stack effect) (Teleszewski & Gładyszewska-Fiedoruk, 2018), and 0.3-metre window vertical movement (Abbas & Gursel Dino, 2022; Yu et al., 2022), coupled with 25% WWR in both Avalon and Canterbury, this significantly reduced carbon dioxide. In optimal Avalon, at 10 l/s/p, the spike from 10% was reduced by 50%; at 7 l/s/p, the spike from 11% dropped to 4.8%, and 3 l/s/p resulted in 4.5% from 12%. Moreover, Canterbury at 10 l/s/p dropped to 0.5%, 7 l/s/p at less than 1%, and 3 l/s/p resulted between 07-1.3%.

5.5 Limitations and Area of Improvement

This study presents insights regarding IAQ and TC positioning with current DQLS V2.0 standards. DQLS V2.0 establishes a solid foundation for classroom environmental quality regarding adaptive comfort, daylight/illuminance, ventilation strategies, carbon dioxide, and energy load (heating and cooling) while presenting opportunities for enhancement through targeted interventions. The standard achieves commendable balance across multiple performance criteria, with specific areas showing potential for improvement.

Thermal Comfort: DQLS V2.0 delivers satisfactory thermal comfort percentages across most climate zones, particularly in moderate regions. The variations observed between northern and southern regions suggest that while the standard provides good thermally balanced performance, strategic ceiling height, window positioning adjustments, WWR%, and a slight increase in R-value in cooler regions can enhance adaptive thermal comfort without compromising other environmental factors. Both classroom typologies achieve acceptable daylight autonomy under DQLS V2.0, with consistent illuminance distribution. The research demonstrates that carefully calibrated window-to-wall ratio reductions (to 25%) can maintain sufficient daylighting while simultaneously improving thermal performance - revealing an opportunity to fine-tune the relationship between these interdependent factors. However, there is a trade-off between illuminance and CSP value. Higher illuminance thus creates thermal discomfort. The limitation of this study is that it does not analyse the significant solar gain and different building and window orientations, creating room for future research. Energy Analysis: DQLS V2.0 presents reasonable energy performance that balances competing demands. The optimisation analysis reveals that modest enhancements to thermal envelope specifications (R-values) and other interventions can yield significant improvements in heating and cooling loads while maintaining efficient parameters, pointing to potential efficiency gains through climate-specific adjustments. However, the high heating load in the northern region and high cooling load in the southern region indicate that future studies can connect it with different window orientations associated with climate-orientated research with enhanced ventilation strategies. The cost implications associated with interventions have not been analysed in future studies. Carbon Dioxide: The ventilation strategies within DQLS V2.0 provide adequate indoor air quality, with Canterbury typology showing better baseline CO_2 management than Avalon. The improved performance achieved through adjusted window operation schedules and increased ceiling height demonstrates that relatively simple interventions can substantially enhance ventilation effectiveness while preserving the standard's core environmental balance. CO_2 management strategies could be enhanced by implementing optimised window operation more frequently schedules and leveraging stack effect for better airflow. The research confirms DQLS V2.0's effectiveness as a comprehensive standard while highlighting how thoughtful, integrated interventions can simultaneously elevate its performance across multiple environmental criteria.

5.6 Conclusion

This comprehensive assessment of DQLS V2.0 across diverse New Zealand climate zones against OECD standards reveals significant strengths and areas requiring strategic intervention. The standard demonstrates remarkable versatility in establishing baseline environmental quality metrics that generally outperform several OECD standards, particularly in thermal comfort and daylighting parameters.

The DQLS V2.0 framework maintains Total Comfort Percentage (TCP) values consistently above 70% across most regions in both Avalon and Canterbury classroom typologies, showcasing its ability to adapt to New Zealand's varied climate conditions. This foundational strength in thermal comfort supports cognitive function and student well-being across diverse geographical locations. Similarly, the daylight autonomy (DA) metrics consistently achieve acceptable thresholds above 47%, with useful daylight illuminance (UDI) values exceeding 67% in both typologies, indicating effective baseline illumination strategies. Still, its impact on thermal comfort has not been analysed.

However, notable limitations emerge in specific performance areas that warrant targeted improvement. The standard exhibits challenges in managing cooling season comfort percentages (CSP), particularly in northern regions where overheating issues are more pronounced. Energy analysis reveals suboptimal performance in heating loads for northern regions (65-70 kWh/m²) and cooling loads in southern regions (21-36 kWh/m²), indicating opportunities for climate-specific calibration. Additionally, the Avalon typology demonstrates higher CO_2 concentration spikes (9-12%) compared to Canterbury (4-5%), suggesting ventilation strategies require typology-specific refinement. Optimisation analysis demonstrates that strategic interventions can significantly enhance DQLS V2.0 performance without compromising its holistic approach. Specifically, adjustments to ceiling height (3.5m), window positioning (0.3m vertical repositioning), window-to-wall ratio reduction (25%), enhanced thermal envelope specifications, and refined ventilation scheduling can yield substantial improvements: TCP increases of 3-17%, CSP reductions of 5-18%, heating load reductions of 6-16%, cooling load reductions of 10-35%, and CO_2 concentration reductions of 10-30% in Avalon block.

These findings affirm that DQLS V2.0 establishes a stronger foundation for classroom environmental quality than comparable OECD standards, particularly in its balanced approach to multiple performance criteria. The standard's comprehensive framework provides a robust platform that, with strategic climate-specific interventions and more holistic analysis incorporating orientation factors, solar gain considerations, window position optimisation, post-occupancy evaluation, and cost implications, can further elevate classroom environmental quality to exceptional levels, balancing the relationship between the improved thermal performance (particularly from height increases) and ventilation effectiveness would strengthen DQLS V2.0's relevance for post-pandemic design.

Future research should explore the interrelationships between building orientation, window configuration, and climate-specific adaptations to refine the DQLS framework further. Additionally, cost-benefit analyses of proposed interventions would provide valuable insights for practical implementation. By building upon DQLS V2.0's strong foundation with these targeted enhancements, New Zealand's educational facilities can achieve optimal environmental conditions that support student learning outcomes while maintaining energy efficiency and sustainability goals.

Chapter 6 Prologue

Having established baseline standards in Chapter 3, compared them internationally in Chapter 4, and developed optimal design solutions through simulation in Chapter 5, this chapter addresses a critical question: are the proposed modifications practical, implementable, and effective according to those who will ultimately design and construct these spaces? Validation transforms theoretical findings into actionable guidance by testing proposed solutions against the expertise of industry professionals.

This chapter presents a comprehensive validation study involving ten New Zealand industry experts with extensive experience in architectural design, building science, and school construction. These professionals assessed the feasibility and practicality of proposed design interventions developed through parametric modelling: increasing classroom height by approximately one meter, adjusting window placement vertically by 0.3 meters, optimizing window-to-wall ratios to 25%, enhancing thermal insulation properties for southern climate zones (Christchurch and Queenstown), and adjusting clothing insulation recommendations. The validation employed a mixed-method approach combining open-ended questionnaires that captured nuanced expert insights with Likert scale assessments that quantified agreement levels across multiple evaluation criteria.

Readers will find three main components in this chapter. First, a detailed methodology section explaining the five-phase validation process, from initial simulation development through expert selection to formal interview procedures, ensuring transparency and replicability. Second, comprehensive results presenting expert feedback organized around three key themes: the appropriateness of simulation methodology used throughout the research, the value of comparing DQLS Version 2.0 against international standards, and the practical implications of each proposed design modification across New Zealand's diverse climate zones.

Third, a discussion synthesizing expert opinions to identify consensus areas, implementation challenges, and regional considerations that influence design decisions.

This validation chapter serves a vital bridging function between research findings and real-world application. Expert feedback reveals not only what works theoretically but what remains feasible given construction realities, cost constraints, and operational requirements. Understanding these practical considerations ensures that the final recommendations presented in Chapter 7 balance evidence-based optimization with implementability, creating guidelines that architects, engineers, and education authorities can confidently adopt to improve learning environments for New Zealand children.

6. Validation of Optimal Indoor Air Quality and Thermal Comfort Design Guidelines for Post-COVID-19 New Zealand Primary School Classrooms

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Abstract

This study presents a comprehensive validation approach for evaluating optimal Indoor Air Quality (IAQ) and Thermal Comfort (TC) design guidelines for post-COVID-19 primary school classrooms across New Zealand's six climate zones. The research employed a mixed-method validation strategy involving ten industry experts who assessed the practicality and effectiveness of proposed changes to the typologies of Avalon and Canterbury Block for primary schools. The validation process utilised both open-ended questionnaires and Likert scale assessments to evaluate key design interventions, including a ~1-meter increase in classroom height, 0.3-meter vertical extension of window placement for all six climate zones and enhanced thermal insulation properties and clothing insulation specifically for climate zones 5 and 6 (Christchurch and Queenstown). These modifications were developed through extensive parametric modelling using Rhino software with Grasshopper and Ladybug tools and applied to two prevalent classroom typologies - the Avalon and Canterbury blocks. The study builds upon a thorough comparative analysis of international standards (ASHRAE 62.1, EN15251, Building Bulletin 99 & 101, CIBSE) against DQLS Version 2.0, focusing on critical variables including temperature requirements, ventilation rates, carbon dioxide levels, classroom dimensions, and occupancy standards. Optimizing classroom environments is crucial for supporting student learning and well-being. This study explores evidence-based design strategies to enhance indoor air quality and thermal comfort in primary school classrooms. Results from the expert validation process revealed varying degrees of practical implementation challenges across different climate zones, with particular emphasis on the special requirements for colder regions. The findings have led to specific recommendations for enhancing DQLS Version 2.0, ensuring its effectiveness in achieving healthy primary school classroom environments while maintaining cost-effective and practical implementation strategies across New Zealand's diverse climatic conditions.

Keywords: Building performance, Classroom design, Indoor air quality, Semi-structured interview, Thermal Comfort.

6.1 Introduction

Indoor air quality (IAQ) and thermal comfort in newer or older buildings significantly influence overall health (mental and physical), performance and day-to-day productivity. In school classrooms, poor indoor air quality and thermal comfort excessively affect children's academic achievement, impacting their cognitive functionality and concentration (Pistore et al., 2020). This study builds upon previous research by addressing critical gaps in understanding IEQ in educational environments. While existing studies have often examined individual environmental aspects, our research aims to provide a more comprehensive and integrated approach to classroom design assessment. In the past few years, the research on IAQ and thermal comfort in educational buildings after COVID-19 has received more attention in primary schools (Kim & de Dear, 2018), with the intent to get a clearer finding of children's interaction and behavioural dependencies with indoor environmental conditions.

Research on Indoor environmental quality (IEQ) in educational buildings has been ongoing for decades. IEQ includes four main domains, namely thermal comfort (TC), indoor air quality (IAQ), visual comfort (VC) and acoustics (Catalina & Iordache, 2012). Most studies focus on individual IEQ domains within school buildings (Pereira et al., 2014). However, this study distinguishes its differentiation by integrating multiple IEQ domains simultaneously, focusing specifically on post–COVID–19 school classrooms and providing a comprehensive, holistic assessment for optimal designing of the IAQ and TC guidelines for the school classroom. For instance, VC is primarily associated with natural daylight quality (Lai et al., 2009), Acoustics relates to noise assessment (Peters, 2015), thermal comfort is linked to windows efficiency and building typology (Eltaweel & Yuehong, 2017) and IAQ is often assessed separately (Rasheed et al., 2024; Bardhan & Debnath, 2018).

The research advances from existing research by implementing a dual validation approach with industry experts addressing DQLS (2.0) and international IAQ and TC design guidelines in six distinct climate zones of New Zealand, followed by expert-driven validation and offering a comprehensive methodology for assessing classroom environmental quality. Recently, there has been a growing interest in the simultaneous assessment of multiple IEQ domains, particularly due to the impacts of the COVID-19 pandemic (Mahdavi et al., 2020). A recent study suggests that evaluating several domains is crucial for comprehensively understanding overall IEQ in educational settings. Hence, holistic studies that examine multiple domains can provide valuable insights into the interconnected factors related to design typology and their impact on individual IEQ domains (Mabdeh et al., 2020).

Previous research in building performance evaluation has primarily focused on occupant feedback and physical measurements, with limited studies incorporating expert validation of design guidelines. Unlike these traditional approaches, our study introduces a novel validation methodology. By combining qualitative and quantitative assessments from industry experts, we provide unprecedented insights into the practical feasibility of design modifications for primary school classrooms. While studies have explored occupant dissatisfaction and adaptive responses in educational environments (Rasheed et al., 2024), there remains a gap in validation methodologies specifically targeting design guidelines through expert consultation. (Hosseini et al., 2017; Kim & de Dear, 2018). Also, the validation of building design modifications and guidelines has traditionally relied on simulation data and occupant feedback, often overlooking the valuable insights that industry practitioners can provide. (Liu et al., 2017; Mishra & Ramgopal, 2015).

This study implements a dual-validation approach, combining qualitative and quantitative assessments from industry experts specialising in school design and construction sites. The approach is particularly relevant for evaluating technical design guidelines, as architects and building professionals possess the practical experience to assess the feasibility of proposed modifications such as increasing classroom heights, optimising window placements, and enhancing thermal insulation and clothing insulation properties. While similar research has focused on various aspects of IEQ, this study takes a comprehensive approach to validating design modifications across New Zealand's six climate zones (Buratti et al., 2018). Furthermore, this study specifically addresses the practical implementation challenges of design modifications (Wang et al., 2018).

New Zealand presents a unique research context due to its diverse climate zones, ranging from subtropical in the north to temperate in the south. The country's heavy reliance on natural ventilation and specific educational infrastructure makes it an ideal setting for investigating post-COVID-19 classroom design guidelines. Moreover, the country's commitment to educational quality and environmental sustainability provides a critical landscape for developing innovative classroom design strategies. The study aims to validate optimal Indoor Air Quality (IAQ) and Thermal Comfort (TC) design guidelines for post-COVID-19 New Zealand primary school classrooms across six climate zones. This study has two objectives: RO1: to validate the developed optimal post-COVID-19 IAQ and TC design guidelines for six climate zones in New Zealand primary school classrooms, and RO2: to recommend improvement opportunities for DQLS version (2.0) to achieve healthy primary school classrooms in New Zealand.

The significance of this research extends beyond immediate design recommendations. By providing evidence-based guidelines, this study can potentially transform:

1. Educational infrastructure design approaches
2. Indoor environmental quality standards for schools
3. Understanding of climate-responsive classroom design
4. Post-pandemic educational space planning

Practical implications include developing adaptive design guidelines that:

1. Enhance children's learning environments
2. Improve health outcomes physically and mentally
3. Provide cost-effective design solutions
4. Support educational resilience in changing environmental conditions

By incorporating open-ended questionnaires and Likert scale assessments from ten industry experts, we provided a comprehensive evaluation framework, particularly valuable for assessing technical specifications within the DQLS Version 2.0 guidelines. This methodology builds upon previous approaches by shifting the focus from occupant feedback to expert validation, offering insights into the proposed design modifications' theoretical effectiveness and practical implementation challenges. This study extends beyond operational considerations to examine the fundamental design elements that can enhance IAQ and TC in post-COVID-19 primary school classrooms.

6.2 Methodology

This study employed a comprehensive mixed-method approach to validate the optimal IAQ and TC guidelines across New Zealand's six climate zones. The validation process was structured into five distinct phases, each building upon the previous to ensure a robust and thorough assessment of the proposed optimal IAQ and TC guidelines.

Phase 1 focused on developing and simulating two primary classroom typologies - Avalon and Canterbury blocks - using DQLS version 2.0 document reference models. These models were created using Rhino modelling software and enhanced with intuitive plugins for simulation purposes. The simulation script incorporated IAQ and TC variables, including construction sets, activity schedules, model construction specifications, and yearly operational data. The analysis script integrated comprehensive evaluation metrics: thermal comfort assessment, ventilation system analysis, daylight analysis, carbon dioxide monitoring, and energy analysis. Additionally, Ladybug tools were utilised to analyse relative humidity, dew point, and dry bulb temperature. This phase included performance testing across all six climate zones using localised weather files and evaluating New Zealand DQLS V(2.0) and international standards (ASHRAE 62.1, EN15251, Building Bulletin 99 & 101, CIBSE).

Phase 2 encompassed the development of numerical tables and the modelling of classroom designs, comparing current specifications with proposed optimal modifications in Rhino software. Phase 3 involved creating validation steps under supervisory guidance, including open-ended and Likert scale questionnaires designed to capture expert insights on the practicality and effectiveness of the proposed optimal IAQ and TC guidelines.

Phase 4 consisted of the careful selection of validation experts. Through comprehensive discussion with the supervisory panel, ten industry experts from New Zealand's architectural sector were identified, each with significant school design experience. The final phase (Phase 5) involved the formal validation process, where each expert participated in approximately 50-minute individual interviews. These sessions included the presentation of simulation findings, a detailed discussion of the optimal IAQ and TC design guidelines and exploring limitations and future research directions. This study ensured strict participant confidentiality and data protection measures. Participation was voluntary, and personal information was kept secure. There were no anticipated risks, and the research received low-risk ethics approval (Ethics Notification Number: 4000027845) from Massey University, with the researcher responsible for ethical conduct. Participants were informed of their rights, including the ability to withdraw at any time without consequence. The expert validation findings are presented in the results chapter, while the limitations and future research implications are discussed in subsequent sections. This methodological approach thoroughly validates the proposed guidelines, combining technical simulation data with expert practical insights to create robust, implementable solutions for New Zealand primary school classrooms in the post-COVID-19 context. Figure 6.1 below shows the flowchart of the validation assessment model.

6.3 Result and Findings

This section explains the findings via semi-structured methods, involving a set of open-ended questions and a Likert scale questionnaire for four individual sections, namely thermal comfort, energy loads, carbon dioxide, and ventilation and proposed optimal IAQ and thermal comfort guidelines to Avalon and Canterbury classroom design changes.

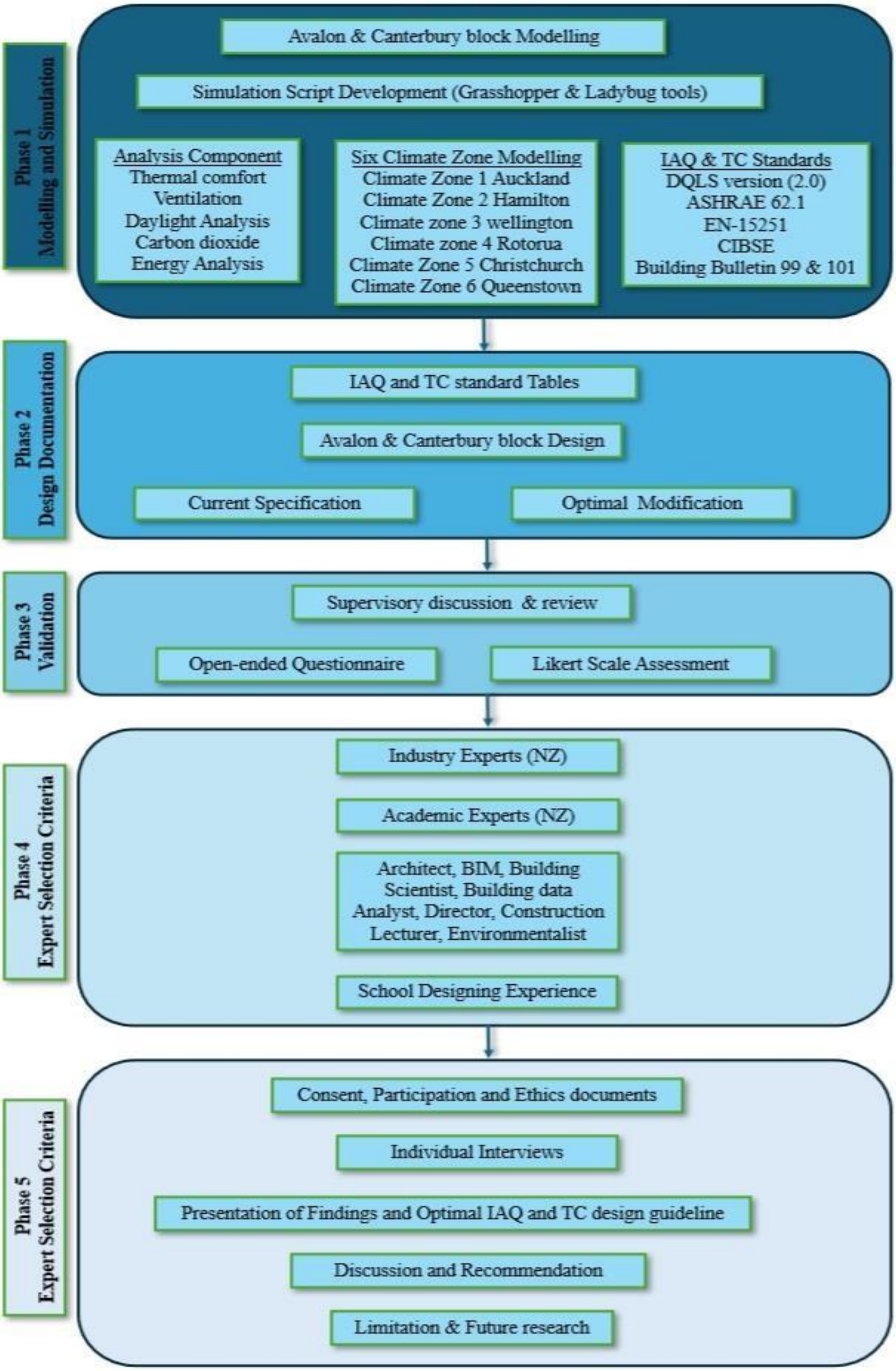

Figure 6.1: Methodology Flowchart

Validation is crucial in building performance research, particularly for evaluating design guidelines and environmental performance metrics (Lucko & Rojas, 2010). Research validity assessment can be divided into qualitative and quantitative methods (Ameyaw et al., 2015) with three types of validity are most commonly used in construction management research: construct, internal and external (Abowitz & Toole, 2010; Rasheed, 2024). The validation process incorporated three key dimensions:

1. construct validity is established by measuring the underlying construct for IAQ and thermal comfort in an indoor classroom environment. The measurement constructs in this study are IAQ and TC influencing parameters, which were identified through a literature review.

2. internal validity is established through comparison of DQLS Version 2.0 with established international standards (ASHRAE 62.1, CIBSE, EN-15251, Building Bulletin 99 & 101), the simulation methodology (tools or software) and parametric modelling approach and identify the potential IAQ and Thermal comfort parameters.

3. external validity is established through industry experts' assessment of proposed design modifications' practicality and effectiveness.

Ten industry experts from New Zealand with extensive experience in various areas of building design provided comprehensive feedback through open-ended questions and Likert scale responses (N. Rasheed et al., 2024). They evaluated the appropriateness of simulation methods, the value of international standard comparisons, and the potential impact of proposed design changes. This multi-faceted validation approach ensured the research findings' credibility, usability, and generalisability across New Zealand's six climate zones while acknowledging practical implementation considerations and local contextual factors.

Table 6.1 below gives the background of each industrial expert's field of relevance to this study and years of experience in their respective area of expertise. The table indicates that each of the ten industrial experts in New Zealand holds significant years of experience with building design, architecture, modelling, building data analysis, sustainable building, etc., which adds to the credibility of the validation phase.

Table 6.1: Background details of validation experts

Industrial Expert ID	Sector	Field /Expertise	Experience
Expert 1	Industry	EECA	4 years
Expert 2	Industry and Academic	Construction Management Professional	6 years
Expert 3	Industry and Academic	Building Information Modelling (BIM)	5 years
Expert 4	Industry	Director at Robertson Architects	25 years
Expert 5	Industry	Architect Ecological Associates	5 years
Expert 6	Industry	Architect VIA Architecture	25 years
Expert 7	Industry	Sustainable Buildings Leader at Aurecon	15 years
Expert 8	Industry	Director and Registered Architect	12 years
Expert 9	Industry	Building Scientist at Beca	5 years
Expert 10	Industry	Architect	7 years

6.3.1 Results of Expert Validation (Open-Ended Questions)

6.3.1.1 Appropriateness and Practicality of Simulation Methodology

The experts generally found the simulation methodology appropriate and practical, though with some notable considerations:

Expert 1 emphasised the importance of validation against empirical data and suggested comparing DQLS and international standards results side-by-side with optimal design changes. Expert 2 was brief but positive, noting that "the software used is new and robust to this kind of study." Expert 3 found the methods "highly appropriate but only moderately practical," citing concerns about potential users' proficiency with computational tools like Rhinoceros and Grasshopper. Expert 4 was particularly impressed with the comprehensive modelling approach, stating it shows "what can be achieved through optimising the design." They suggested developing a simplified tool to make the methodology more accessible to industry practitioners. Expert 5 provided detailed feedback, highlighting the methodology's value in simulating real classroom conditions while noting the importance of considering cost-effectiveness in practical implementation.

Expert 6 found the methodology "reasonable and appropriate" based on the provided description. Expert 7 considered the approach appropriate for the two standard designs but questioned how the assessment might address additional classroom designs used across New Zealand, particularly modern learning spaces. Expert 8 considered the approach robust and technical, particularly with parametric modelling. Additionally, the methodology could be strengthened by analysing seasonal variations. Expert 9 considers a well-structured approach, particularly through its comprehensive integration of multiple environmental parameters. I suggest incorporating more dynamic occupancy scenarios to reflect real-world classroom usage patterns. Expert 10 provided feedback, highlighting that methodology demonstrates robust technical rigour in modelling classroom environments. Rhino with Grasshopper and Ladybug tools are used to assess environmental parameters. I suggest strengthening the methodology by incorporating more detailed operational schedules to reflect classroom usage patterns.

6.3.1.2 Value of Comparing DQLS (2.0) with International Standards

The experts unanimously agreed on the value of international standard comparisons:

Expert 1 emphasised how the comparison validates DQLS framework effectiveness and identifies areas for improvement. Expert 2 viewed it as "a good approach" for finding potential changes or discrepancies. Expert 3 highlighted its relevance for determining NZ guidelines' effectiveness and potential adjustment needs. Expert 4 stressed the importance of using international standards wherever possible, noting they are "well-tested standards around which tools have been developed." Expert 5 provided comprehensive feedback, noting the value of identifying best practices while cautioning about the need to consider New Zealand's unique context.

Expert 6 emphasised the importance of benchmarking against recognised international standards, particularly given New Zealand's tendency to "exceptionalise our standards." Expert 7 offered unique insight as someone familiar with DQLS development, noting that some international standard recommendations were not accepted in v2.0 due to cost and complexity concerns. Expert 8 explains that comparison becomes especially relevant in the post-COVID context, where international best practices for classroom ventilation have evolved significantly. The analysis helps position New Zealand's standards within the global context while acknowledging local climatic and architectural considerations. Expert 9 states that comparative analysis is particularly valuable in identifying areas where New Zealand's approach either leads or could benefit from international best practices. The comparison demonstrates how regulatory frameworks address similar challenges in varying climatic conditions. Expert 10 highlights that analysis with international standards provides a crucial context for evaluating DQLS 2.0's effectiveness. This international perspective is essential for ensuring our schools meet world-class standards while addressing local environmental conditions.

6.3.1.3 Impact of Proposed Classroom Design Changes

The experts provided varied perspectives on the design modifications:

Expert 1 noted significant positive impacts of the proposed changes on indoor air quality and thermal comfort, emphasising the importance of each design element. The ~1m height improvement stands quite effective with context to airflow within the classroom, keeping natural air circulation. Window adjustment appears to be an improvement strategy, but it can cause heat loss and gain issues if the glare and solar gain are not assessed well. The R-value shows significant improvement in maintaining thermal comfort, but the cost needs to be reassessed with its modification. Expert 2 focuses on modification as a balanced approach, stating that ~1m height improves circulation and creates a room with more space for better airflow. Window placement is noteworthy, connecting with dual effective daylight and cross ventilation measures, and heat gain and loss are to be measured properly, raising concern about the implications of improving R-value and clothing insulation.

Expert 3 noted that the increased room height provides a larger air volume, which inherently helps maintain better air quality. At the same time, the adjusted window placement enhances the stack effect for natural ventilation. The R-value modifications are particularly crucial for the southern regions. One notable strength is how these changes work synergistically – the combination of height increases and window placement, WWR optimisation creates more effective air movement patterns than either modification alone. Expert 4 emphasised that improved performance is possible "with better design that doesn't add higher cost," though noting height changes might have cost implications. The ~1-meter increase in classroom height is particularly significant as it improves the stack effect for natural ventilation and creates a thermal buffer zone that can help stabilise indoor temperatures throughout the day, providing more flexibility for mechanical systems integration when needed. The 0.3-meter upward adjustment of window placement is theoretically sound for enhancing cross-ventilation. This must be carefully balanced with glare control and solar heat gain, especially in north-facing classrooms. Enhanced R-values for building envelope components are crucial, suggesting improvement for colder regions can significantly help reduce heating loads, and the cost of retrofitting should be assessed well. The clothing insulation adjustment is a practical solution. However, its success heavily depends on clear communication with school administrators about seasonal dress code policies and the provision of adequate storage solutions for additional clothing items.

Expert 5 provided a detailed analysis of each design element's potential benefits and limitations, emphasising the need to consider practical implementation challenges. The proposed design modifications show the ability to enhance both IAQ and thermal comfort. The ~1-meter height increase appears particularly effective for natural ventilation. The window placement modifications could significantly improve air circulation patterns, but glare and solar gain should be taken in parallel. The R-value adjustments seem well-calibrated for New Zealand's climate variations, but detailed consideration must be given to the associated construction costs and structural implications and acknowledged benefits but cautioned about relying on human behaviour for elements like clothing choices. Expert 6 states that the proposed design modifications are well-conceived but require careful consideration in implementation. The ~1-meter height increase is particularly interesting – in my experience, similar modifications can lead to approximately 20-25% improvement in air circulation patterns, especially beneficial during peak occupancy periods. Structural considerations could impact construction costs by roughly 10%, depending on the building method used. The window placement adjustment of 0.3 meters upward is a subtle yet effective change, improving ventilation effectiveness by creating a better pressure differential. The improvised R-value is important for climate zones 5 and 6 and could reduce heating demands by a significant percentage during the cold season; however, the challenge is associated with maintaining in highly humid zones over time. Clothing insulation change is a pragmatic application depending on seasonal variations and school authorities.

Expert 7 characterised the improvements as an "optimal design strategy" and suggested investigating additional mitigation strategies like external blinds and shading elements. The ~1meter height positively impacts air circulation, but the additional cost with refurbishment and heating loads during cold months. R-value improvisation can significantly enhance overall thermal comfort, but the recommendation of clothing insulation depends on children's acceptability with behavioural conditions. Expert 8 characterised the proposed design modifications as showing promising potential for improving classroom environments. The ~1meter height increase would significantly enhance stack ventilation effects. Window placement modifications are particularly clever, optimising natural ventilation without requiring extensive structural changes. R-value improvements for climate zones 5 and 6 are essential in recommending maintenance considerations. The holistic approach to combining passive and active strategies demonstrates a thorough understanding of the principles of building physics.

Expert 9 states that modification reflects a sophisticated approach toward building physics. The increased ceiling height will impact better airflow and create a thermally comfortable indoor environment via natural airflow. Window placement was considered to impact changes in seasonal variations, impacting heat gain and loss associated with energy loads. Clothing insulation is highly dependent on school administration and effective communication with teachers as it can provide comfortable conditions in cold seasons. There is not much detailed information in the context of R-value and commented costs might be associated with it, as well as challenges for climate zones 5 and 6. Expert 10 explains the proposed changes as a viable option, increasing the ~1m height as it can be helpful with the air stratification process and maintain natural airflow. Still, it shows concern that window placement can be equally effective if glare and solar gain are controlled. The R-value improvements for climate zones 5 and 6 demonstrate good thermal performance enhancement, considering the cost associated with modification and clothing insulation provide a practical adaptive approach, especially relevant for New Zealand's varied climate conditions.

Additionally, to open-ended assessments, the experts were asked to evaluate and provide feedback on various aspects of the proposed methodology for designing optimal IAQ and TC findings using a Likert scale questionnaire. For simplicity of analysis, the Likert scale questions used a 5-point scale (1-Strongly Disagree, 2-Disagree, 3-Neutral, 4-Agree, 5-Strongly Agree). The mean scores based on expert responses are presented below in Table 6.2.

As depicted in Table 6.2, the average mean value score for each variable assessed to develop optimal IAQ and TC guidelines for primary school is within the range of 3.5 to 4.2 out of 5. This states that the experts viewed the methodology and relevant result findings as good practice i.e., ‘agree’ or ‘strongly agree’.

6.4 Discussion

This study's comprehensive analysis of expert evaluations reveals critical insights into classroom environmental design modifications and their practical implications. Through a detailed examination of ten expert assessments, several key themes emerged regarding the proposed changes to room height, window placement, R-value improvements, and clothing insulation strategies. The experts' evaluations demonstrated a strong consensus on certain aspects while highlighting important implementation considerations that warrant careful attention. Integrating DQLS framework comparisons with international standards and robust methodological assessments using advanced computational tools provided a multi-faceted perspective on optimising classroom environments for improved indoor air quality (IAQ) and thermal comfort (TC).

6.4.1 Appropriateness of Simulation Methodology

In terms of assessment for the simulation methodology appropriateness, the experts used terminology like “robust”, “technical”, and “appropriate”, suggesting both “comprehensive” and “valid”. The simulation methodology's appropriateness received consistently positive feedback, with experts highlighting its comprehensive approach, particularly the effectiveness of parametric modelling through Rhinoceros and Grasshopper.

The experts generally supported the technical robustness of the methodology while raising important considerations about its practical implementation. A clear divide emerged between those focusing on technical merits and those emphasising practical limitations. Experts 1 and 2 highlighted the methodology's technical validity, with Expert 1 specifically emphasising the importance of empirical validation through side-by-side comparisons. Experts 3 and 4 brought attention to a crucial implementation challenge: the complexity of computational tools like Rhinoceros and Grasshopper, with Expert 4 specifically recommending the development of simplified tools for industry practitioners. Experts 5 and 6 found the methodology appropriate but emphasised different aspects - Expert 5 focused on cost-effectiveness considerations, while Expert 6 affirmed the general approach. Expert 7 raised a unique concern about the methodology's applicability to diverse classroom designs, particularly modern learning spaces. Experts 8, 9, and 10 provided more nuanced technical feedback, suggesting specific improvements: Expert 8 emphasised the need for seasonal variation analysis, while Experts 9 and 10 advocated for incorporating more dynamic occupancy scenarios and operational schedules. A notable consensus emerged around the methodology's technical merit, with Experts 2, 4, and 8 specifically praising its robustness. However, a recurring theme across multiple experts (3, 4, 5, and 7) was the need to balance technical sophistication with practical usability, suggesting that future developments should focus on making the methodology more accessible while maintaining its analytical rigour.

Table 6.2: Likert scale mean score

Variables (Likert Scale)	Mean Score
Thermal Comfort Assessment	
TCP	4.2
HSP	4.1
CSP	4.2
Thermal Comfort (CZ 5 & CZ6)	3.9
Energy Performance Evaluation	
Cooling & Heating Load	3.7
Infiltration Load	3.5
Natural Ventilation Load	4.1
Indoor Air Quality Assessment	

CO_2 Concentration – six climate zone	3.8
Ventilation rate – six climate zone	4.0
CO_2 Concentration (International standard)	4.1
Overall CO_2 & ventilation rate	3.7
Proposed Optimal Design	
Classroom height ~1m)	3.9
Windows move (vertically – 0.3 m)	4.0
Window-to-wall ratio (WWR)	4.0
Clothing insulation	3.7
R-value (building envelop)	4.1

6.4.2 Value of Comparing DQLS (2.0) with International Standards

In evaluating the value of international standard comparisons for DQLS 2.0, experts employed terms like "essential", "valuable", and "critical", indicating both "significance" and "necessity". The comparative analysis approach received overwhelmingly positive endorsement, with experts emphasising its role in validation and improvement identification. Expert feedback particularly highlighted the framework's ability to benchmark against established global standards while acknowledging the importance of considering New Zealand's unique contextual requirements. The experts strongly consented to the value of international standard comparisons with DQLS (2.0) while emphasising different aspects of their importance.

All experts viewed the comparative analysis as beneficial, but their focus areas varied significantly. Experts 1, 2, and 3 emphasised the framework's validation aspect, with Expert 1 specifically highlighting its role in identifying improvement areas. Expert 4 uniquely stressed the practical benefits of utilising established international standards, particularly regarding available tools and testing procedures. Expert 5 provided a balanced perspective, acknowledging the value of identifying global best practices while emphasising the importance of considering New Zealand's specific context. Expert 6's observation about New Zealand's tendency to "exceptionalise" standards added a critical cultural dimension to the discussion. Expert 7 offered a valuable insider perspective on DQLS development, revealing how cost and complexity concerns influenced the rejection of certain international recommendations in version 2.0. Experts 8 and 9 brought attention to contemporary relevance, particularly highlighting post-COVID considerations and the evolution of ventilation standards. Expert 8

specifically emphasised the importance of local climatic and architectural considerations, while Expert 9 focused on regulatory framework comparisons across different climatic conditions. Expert 10 rounded out the discussion by emphasising the balance between meeting world-class standards and addressing local environmental needs. The collective expert opinions suggest that while international comparisons are valuable for benchmarking and improvement, successful implementation requires careful consideration of local contexts and practical constraints.

6.4.3 Feasibility of Optimal IAQ and TC Design Standards

Regarding the feasibility of proposed design modifications for optimal IAQ and TC, experts used descriptors such as "promising", "effective", and "practical", suggesting both "viability" and "implementability". The design modifications received detailed scrutiny, with experts consistently acknowledging their potential benefits while raising important considerations about implementation challenges.

The expert evaluations reveal widespread agreement on the potential benefits of the proposed classroom design modifications while emphasising critical implementation considerations. All ten experts consistently endorsed the ~1-meter height increase as beneficial for air circulation and thermal comfort, with Expert 6 specifically quantifying a 20-25% improvement in air circulation patterns. However, Experts 4, 6, and 7 raised concerns about associated construction costs and heating loads, estimating potential cost increases of approximately 10%. The 0.3meter window placement adjustment received broad support, with Experts 3, 6, and 8 particularly emphasising its effectiveness for stack ventilation and natural airflow. Nevertheless, Experts 1, 4, and 10 stressed the critical need to manage glare and solar gain concerns. Regarding R-value improvements, Experts 3, 6, 8, and 10 specifically highlighted their importance for climate zones 5 and 6, though Experts 6 and 9 noted challenges in maintaining effectiveness in humid conditions and associated cost implications. The clothing insulation strategy garnered mixed responses, with Experts 4, 5, 6, and 9 emphasising its practicality but noting heavy dependence on school administration cooperation and clear communication. A notable observation from Experts 3 and 7 was the synergistic effect of combining these modifications, suggesting their collective impact exceeds individual contributions. Expert 7's suggestion for additional mitigation strategies like external blinds and shading elements stood out as a unique contribution. The overall consensus indicates that these modifications offer significant potential benefits while requiring careful consideration of regional climate variations, implementation challenges, and cost implications.

6.4.4 Limitations and Future Research

The study acknowledges several limitations that warrant consideration. While the computational methodology using Rhinoceros and Grasshopper demonstrated robust technical capabilities, its complexity poses accessibility challenges for industry practitioners. The analysis focused primarily on two standard classroom designs, potentially limiting its applicability to modern learning spaces and diverse architectural configurations across New Zealand. Additionally, the current methodology's static occupancy patterns may not fully capture the dynamic nature of classroom usage.

Future research opportunities include developing simplified assessment tools that maintain analytical rigour while improving accessibility for practitioners. Studies investigating the methodology's applicability to diverse classroom typologies, particularly modern learning environments, would enhance its practical value. Research incorporating more dynamic occupancy scenarios and detailed operational schedules could better reflect real-world conditions. Investigating seasonal variations' impact on design modifications and their effectiveness across different climate zones would provide valuable insights. Additionally, empirical validation studies comparing DQLS (2.0) predictions with actual performance data would strengthen the framework's reliability. Future work should also explore cost optimization strategies for implementing design modifications, particularly balancing improved performance and economic feasibility. Integrating post-occupancy evaluations could provide valuable feedback on the real-world effectiveness of proposed design changes.

6.5 Conclusion

The findings from this research demonstrate the complex interplay between design modifications, technical feasibility, and practical implementation in achieving optimal classroom environments. This study has identified promising opportunities and significant challenges in enhancing indoor air quality and thermal comfort in New Zealand classrooms through systematic analysis of expert evaluations, methodology assessment, and framework comparisons. The research reveals that while technical solutions show considerable potential for improvement, their successful implementation requires careful consideration of multiple factors, including regional climate variations, cost implications, and operational practicality. The synthesis of expert opinions across various study aspects - from specific design modifications to methodological approaches - provides valuable insights for future developments in classroom environmental design.

The comprehensive analysis of expert evaluations reveals significant potential for improving classroom environments through targeted design modifications. The proposed ~1-meter height increase demonstrates particular promise, with experts consistently noting its effectiveness in enhancing air circulation patterns and thermal comfort (Chen & Mak, 2021; Kamar et al., 2019; Yang et al., 2016). Quantitative assessments suggest potential improvements in air circulation, though this benefit must be weighed against an estimated 10% increase in construction costs (Kamar et al., 2019). The 0.3-meter window placement adjustment emerges as a cost-effective strategy for enhancing natural ventilation, particularly when integrated with careful consideration of glare control and solar gain management (Pereira et al., 2022; Ruonan Wang et al., 2020; Ran Wang et al., 2020).

The comparison of DQLS (2.0) with international standards provides crucial validation while highlighting opportunities for framework enhancement (Arya et al., 2024; E. Rasheed et al., 2024). This benchmarking exercise reveals the robustness of New Zealand's approach and areas where international best practices could inform local standards, particularly in post-COVID contexts where ventilation requirements have evolved significantly. The methodology's technical rigour, particularly in parametric modelling using Rhinoceros and

Grasshopper, demonstrates sophisticated analytical capabilities while highlighting the need for more accessible industry tools (Bakmohammadi & Noorzai, 2020; Hakim et al., 2021; Van Tung, 2021).

The study emphasises the importance of holistic design approaches, where individual modifications work synergistically to create more effective environmental improvements than isolated changes. The R-value improvements show particular promise for climate zones 5 and 6, though implementation challenges in humid conditions require careful consideration (Baglivo et al., 2017; Su, 2017; Tagliabue et al., 2018). The clothing insulation strategy, while practical, highlights the crucial role of stakeholder engagement and clear communication in successful implementation (de la Hoz-Torres et al., 2023; Ter Mors et al., 2011; Wang et al., 2019).

The findings suggest that successful classroom environment optimisation requires a careful balance between technical innovation and practical implementation. While the proposed modifications demonstrate significant potential for improving indoor environmental quality, their successful implementation depends on thoughtful consideration of local contexts, climate variations, and economic constraints. The research underscores the value of evidence-based design approaches while acknowledging the need for flexible solutions that adapt to diverse architectural configurations and evolving educational needs. This balanced perspective provides a foundation for future classroom design developments, prioritising performance optimisation and practical feasibility in educational buildings.

7. Conclusion and Recommendations

7.1 Introduction

The impact of poor IAQ and TC on primary school students' health, well-being, and cognitive performance cannot be overemphasised. Providing an optimal learning environment is paramount. This chapter contains the concluding thoughts of this study. It summarises the rationale for the study, research aim, questions and objectives (Chapter 1), the methods applied with each objective, and the tools and techniques employed for data analysis. This study has produced key findings regarding indoor air quality, thermal comfort, ventilation and carbon dioxide in New Zealand primary school classrooms, particularly focusing on the post-COVID-19 context.

Indoor Environmental Quality (IEQ) encompasses four critical components that significantly impact building occupants' health: lighting quality, thermal conditions, acoustics, and air quality (Catalina & Iordache, 2012). These elements are fundamental to constructed environments as they directly affect visual perception, sound management, temperature regulation, and energy efficiency (Aturupane et al., 2013; Barrett & Zhang, 2009). In educational settings, these environmental factors require particular attention because classroom conditions directly influence students' cognitive function, attention span, and overall educational engagement (Pellegrino et al., 2015).

Corresponding to Andamon et al. (2019), students spend up to 90% of their developmental years indoors at school, accumulating roughly 13,000 hours throughout their academic journey from preschool to Standard 12. Within New Zealand, children accumulate approximately 900 hours annually in school buildings. Throughout their complete educational trajectory (years 1-13), students spend roughly 11,700 hours within school premises, constituting approximately 15% of their conscious existence (Ackley, 2021). Given this substantial temporal investment, the quality of indoor environments in educational settings remains a persistent focus for researchers, educational stakeholders, and parental communities (Bennett et al., 2019; Yassin & Pillai, 2019). Hence, providing optimal Indoor Environmental Quality (IEQ) in these spaces is crucial (Fathi & O'Brien, 2023).

As discussed in Chapter 1 (see section 1.1), the popularity of IEQ studies in school premises stems primarily from two critical considerations: classroom spaces typically contain a high number of young occupants who experience prolonged exposure to contaminants originating from various internal and external sources (Chithra & Nagendra, 2018). Additionally, educational infrastructure frequently receives inadequate maintenance oversight and sustainability assessment, which often exhibits high rates of viral transmission and illness among students. This results in documented substandard IEQ conditions in school spaces across different geographical contexts. The intersection of vulnerable populations and the prevalence of health issues directly attributable to poor indoor environmental quality creates compelling justification for continued scholarly examination of this domain..

In New Zealand, insufficient ventilation in educational environments represents a significant public health concern. Carbon dioxide concentration is a surrogate indicator for assessing classroom air exchange adequacy (Boulic et al., 2022). Suboptimal ventilation metrics in New Zealand, particularly prevalent during winter months in New Zealand educational facilities, potentially compromise respiratory health outcomes (Smedje & Norbäck, 2000; Wang, 2020).

With approximately 90% of New Zealand classrooms utilising natural ventilation through operable windows, the ventilation effectiveness rests upon teachers' intuition and initiative. However, research survey data indicates that fewer than 50% of class teachers utilise window ventilation during instructional periods (Wang, 2020). This creates substantial challenges for maintaining adequate air exchange in densely populated environments, presenting challenges for achieving appropriate ventilation metrics and environmental quality standards (McIntosh, 2011). New Zealand exhibits particularly concerning statistics regarding asthmatic conditions and severe allergic manifestations among students and adult populations (Murphy et al., 2023). Escalating asthma prevalence and health complications among school-aged children demonstrate significant associations with inadequate ventilation infrastructure in educational facilities (Daisey et al., 2003; Mendell & Heath, 2005). Inadequate IAQ and TC impact learning capacities and contribute to respiratory pathologies, with asthma being particularly prevalent among school-aged children (Norbäck & Nordström, 2008; World Health Organization, 2010). New Zealand schools rely on natural ventilation, which leads to higher levels of CO2. Research (McIntosh, 2011) from New Zealand exhibited an average CO2 level exceeding ~1000 ppm in 37 per cent of classrooms for most of the day while operational in school.

During the March 2022 peak of COVID-19 in New Zealand, transmission continued at elevated levels throughout the school year. NZ Ministry of Health epidemiological statistics indicated that education professionals and childcare staff were disproportionately affected, with infection rates of 41% and 38%, respectively—the highest among all occupational categories (Ministry of Health, 2022). Hence, integrated and robust strategic interventions and protocols in school spaces are required to minimise the potential to become a rapid transmitter of serious infectious diseases in future (Kvalsvig et al., 2023). Additionally, these interventions should account for diverse architectural configurations, window placement, building orientations, volume occupant density, and design envelopes that characterise the educational infrastructure in many regions (Aguilar et al., 2021)

Hence, the primary aim of this area of study is to develop IAQ and TC best practices for post-COVID-19 in New Zealand for six climate zones through building performance assessment of IEQ parameters to deliver occupant comfort, satisfaction, health, and well-being while establishing preparedness for future pandemic scenarios and minimise the viral infection. The following objectives were placed to develop the best practices via optimal design solutions to achieve the aim.

1. *To critically evaluate DQLS v1.0 to DQLS v2.0 and DQLS v2.0 with international standard*
2. *To ascertain the suitability of current IAQ and TC guidelines in local and international standard*
3. *To design the optimal IAQ and TC guidelines (best practices) for New Zealand primary school classrooms*
4. *To validate the developed optimal IAQ and TC guidelines (best practices)*
5. *To recommend improvement opportunities apart from scientific interventions for a healthy and optimal indoor environment in classrooms*

Beyond summarising the research journey, this chapter critically interprets the significance of the findings for New Zealand's educational infrastructure, discusses their generalizability and limitations, examines the short- and long-term impacts on policy and practice, and identifies robust research directions needed to strengthen this emerging field. The convergence of pandemic preparedness with considerations of IAQ, Thermal Comfort, and student well-being positions this work at a critical juncture for educational facility design in New Zealand and comparable contexts globally.

7.2 Summary of Research Findings

7.2.1 Critically evaluate local DQLS (v1.0 to v2.0) and DQLS v2.0 to international standards.

The comparative analysis of both DQLS v1.0 and v2.0 provided insights into the response of the NZ Ministry of Education towards mitigating the decade of poor IAQ and TC in classrooms. The comparison showed a swift move from designing for fit-for-purpose and usability of learning spaces and academic outcomes in DQLS v1.0 to non-negotiable standards for indoor air quality and thermal comfort in DQLS v2.0.

At the start of this study, the DQLS v1.0 was the only reference document for the classroom's IAQ and TC design. The study intended to critically analyse this document and compare it with international standards to determine its appropriateness for a post-COVID classroom. While the analysis and comparison were ongoing, the upgrades to the IAQ and TC requirements were implemented in 2022. As such, examining these upgrades and ascertaining their robustness was necessary while highlighting improvement opportunities.

In v1.0, the iteration outlined technical specifications for designers developing appropriate educational spaces that fit the purpose, including provisions for flexible learning spaces (FLS) that facilitate innovative learning environments (ILE) aligned with national curriculum standards. On the other hand, v2.0's comprehensive revision demarcated between non-negotiable standards and flexible design recommendations. It significantly improved performance requirements across air quality indicators, thermal regulation metrics, temperature (overheat) limitations, and ventilation delivery specifications targeted at academic outcomes and healthy well-being. This revision ensured non-negotiable IAQ, TC, and ventilation thresholds for a better classroom indoor environment (Tables 3.1 and 3.2). These thresholds include maintaining the temperature within the 18°C-25°C, and relative humidity between 35-

70%, ventilation rates between 8-10 l/s/p, minimising the window-to-wall ratio between 25-35% and carbon dioxide for 800 ppm, 1250 ppm and 2000ppm classroom size ~ 70 m^2, occupants' density 2.3 m^2, R-value (roof, wall, ceiling, windows), and occupancy schedule (9 am to 3:30 pm) (see Chapter 3). Highlighting these changes enabled the identification of the similarities and differences within both versions of DQLS documents. It evidenced the improvements made towards providing the appropriate learning indoor environment for Tamariki (children).

A further analysis was required to ensure that the changes in DQLS v2.0 aligned with international standards and would enable optimal indoor air quality and thermal comfort for a post-COVID classroom design. A comparison was carried out between v2.0 and international standards for IAQ and TC in OECD countries. Table 4.1 in Chapter 4 showed that NZ DQLS v2.0 standards differed slightly from most OECD countries' standards. Specifically, NZ DQLS v2.0 stood close to international temperature and ventilation standards. However, significant differences were seen in occupants' density, which is closely associated with ventilation rate and CO2 concentration.

The NZ DQLS v2.0 standards stipulated a range similar to WHO AQG, Building Bulletin 101, and EN 15251 standards for temperature. While the minimum CO_2 level is the same as CIBSE and EN 15251, the maximum CO_2 levels differ significantly. For ventilation rate, the NZ DQLS v2.0 standard is closely aligned with the WHO AQG standard and CIBSE standards but higher than the ventilation rate specified in ASHRAE 62.1 and EN 15251. For occupancy, occupant density and room size, the standards differed significantly. While ASHRAE 62.1 and BB 99 specified the occupancy and occupant density required in particular classroom sizes, CIBSE only identified the required occupant density. EN 15251 specified the occupancy and occupant density, while NZ DQLS only noted the required occupancy for classroom size. The occupant's density required in DQLS v2.0 is at baseline with international standards with 2.3 m^2, and the CO2 minimum value is closely aligned with the international range of healthy 800 ppm, whereas the maximum permissible peak concentration allowed is 2000 ppm in a day.

There are implications with these requirements. Firstly, the 2000 ppm CO2 maximum permissible peak concentration falls outside international standards and has the potential to enable viral transmissions even within short periods. Studies show that when CO_2 exceeds 1000–1200 ppm**,** rebreathing of air increases — and with it, a likely buildup of airborne particles (Iwamura et al., 2024; Wilson et al., 2023, Lyu et al., 2022). Secondly, designing educational spaces for better quality requires a 3 to 4 m2 minimum space between children to achieve healthy IEQ. Classrooms with a 2.3 m2/p occupant density will require more fresh air circulation to maintain optimal environmental conditions for children (Korsavi et al., 2020). In addition, the present norm-keeping cost and salary ratio allows a single teacher for 30 children. Henceforth, to achieve healthy indoor environmental quality in a better/quality learning classroom, the ideal area with a single teacher and 30 students should be around 90 to 120 m2 instead of 70 to 75 m2 (Ministry of Education, 2016). Thus, to efficiently manage the occupant density without minimising the occupant number and increasing the volume of the classroom for more airflow to minimise CO_2, the study proposed to increase the height of the classroom and reduce the CO2 maximum permissible peak concentrations, especially for a post-COVID classroom.

7.2.2 Ascertain the current suitability of IAQ and TC in local and international standards and develop optimal best practices (IAQ and TC) for NZ primary school classrooms.

To further ascertain the appropriateness of the IAQ and TC requirements in DQLS v2.0, this study employed simulation techniques followed by parametric modelling. The purpose was to illustrate the performance of these requirements for the 2 sample classroom blocks across the 6 climate zones in NZ. Rhino 7 simulation software was selected based on the highly cited scholarly articles reviewed (see section 5.2.3). The software selection involved a comparative analysis of available simulation software and evidenced why the Rhino 7 (LBT tools) best fit the simulation required (see Figure 5.3). The simulation methodology, document analysis, content analysis, literature review, descriptive statistics and findings from Chapter 3 and Chapter 4 enabled the identification of the significant necessary information for parametric modelling of IAQ and TC with detailed information (see Tables 5.3, 5.4, 5.5, 5.7 and 5.8) in Chapter 5. The parameters (classroom design reference (L*W*H)), construction features (foundation, roof material, flooring, wall, windows and doors, year), occupancy, classroom size, temp, RH, ventilation rate, CO_2, WWR%, R-value (roof, wall, floor and windows) orientation used in the study are based on local and international standards. The constant parameter values (CO2 rate, metabolic rate, occupancy schedule, PPD value, and Clo) used are based on a literature review. The selection of various parameters is based on scholarly articles that analysed IAQ and TC using parametric modelling either in a single domain of IEQ or multiple domains of IEQ. Following the parametric approach to identify the current IAQ and TC workability, metrics for assessing the significance of adaptive thermal comfort (TCP, HSP and CSP), energy analysis (Heating and Cooling load), daylight (cDA and UDI), and carbon dioxide (ppm) findings are provided in Tables (5.9, 5.10 and 5.11) in Chapter 5.

7.2.1.1 Adaptive thermal comfort and daylighting

The comparison of Avalon and Canterbury blocks against DQLS v2.0 and international standards reveals significant insight into the suitability of current IAQ and TC non-negotiable mandatory requirements against all OECD benchmarks across all six climate zones of New Zealand. Adaptive thermal comfort and daylight analysis findings are exhibited per the assessing metrics established in Chapter 5. Avalon blocks adaptive thermal comfort (TCP) in all six climate zones achieved a superior thermal comfort range of ~80% in the northern region and ~70% in the southern region. ASHRAE 62.1 achieved ~70 % in the northern region and ~ 65 % in the southern region. CIBSE achieved ~ 75% in northern and ~70 % in southern regions. While EN15251 showed a similar trend with CIBSE ~75 % in northern regions, it was slightly better than CIBSE ~ 70% in southern regions. In contrast, BB 99 & 101 showed diverse results with better performance in some northern regions ~ 75% (HAM & ROTO), WELL and CHCH (~70%) and QTN 65%.

The Canterbury Block (TCP) performed slightly lower than the Avalon Block in DQLS v2.0. The northern region (~75 %) and southern region varied results with (WELL ~75%) and CHCH and QTN (60-65%). ASHRAE 62.1 exhibits ~70 % in the northern region and 65% in the southern regions. While CIBSE performed similarly to DQLS v2.0 (~ 75 %) in the northern and southern regions except QTN (~55%). EN15251 showed fluctuating results in the northern region (AKL & HAM with ~ 75% & ROTO with ~70%); in the southern region, it performed significantly lower than all other standards. BB 99&101 showed a similar trend to DQLS v2.0 in the northern region ~ 75%, while varied results in the southern region (WELL with ~75 %, CHCH ~65 % and QTN similar to EN15251 ~ 50%). Whereas the Canterbury block for DQLS v2.0 in the northern region shows ~ 80%, and in the southern region, it shows varied results with WELL ~ 70%, CHCH & QTN ~75%.

Avalon block Cooling sensation percentage (CSP) value with DQLS v2.0 in the northern region is ~ 15%, while in the southern region, varied results with WELL and QTN ~ 20% and CHCH ~ 25%, respectively. ASHRAE 62.1 achieved ~ 27 % in AKL and HAM and slightly higher in ROTO ~ 35%, while in the southern region ~ 30%. CIBSE exhibits ~ 30% in AKL and ~ 23% in HAM & ROTO, whereas in the southern region, ~ 30 %. EN15251 showed ~ 30% in AKL and ROTO while ~ 20% in HAM and in the southern region ~ 32%. BB 99&

101 had high CSP in AKL ~ 25%, HAM and ROTO ~15%, whereas in the southern region fluctuating results, in WELL ~ 20%, while in CHCH ~ 27% and QTN ~ 38%. On comparing it with Canterbury, DQLS v2.0 in the northern region showed diverse results with AKL ~ 14%, HAM ~ 12% and ROTO ~ 20%, while in the southern region ~ 29 % in Well, and ~15% in CHCH and QTN. ASHRAE 62.1 shows ~ 20% in the northern region and ~ 22 in the southern region, with CHCH ~ 28%. CIBSE exhibits ~ 16% in AKL and ROTO, and ~ 11 in HAM, whereas in the southern region ~ 20 % in WELL and CHCH, ~33 % in QTN. EN15251 shows ~ 15% in AKL and HAM, ~25% in ROTO, in the southern region, ~24% in WELL, ~30% in CHCH and ~40% in QTN. BB 99&101 shows ~ 11 % in AKL and ROTO, ~ 7 % in HAM, whereas in the southern region ~ 16% WELL, ~ 25 in CHCH and ~ 30 in QTN.

The daylight (DA) in Avalon block DQLS v2.0 showed ~50% in the northern region, while in the southern region except WELL (~45%), CHCH and QTN ~ 48%. In contrast, the Canterbury block in the northern region showed ~52% in AKL and HAM, ROTO ~47%, and in the southern region ~ 48% in WELL and CHCH, QTN showed ~ 44%.

The useful daylight illuminance (UDI) in Avalon block DQLSv2.0 showed ~ 70 % in the northern region and ~ 65% in the southern region. While Canterbury in the northern region showed ~ 69% and in the southern region ~ 66% in WELL and CHCH and ~ 62% in QTN.

7.2.1.2 Energy Analysis

The Comparison of energy load between Avalon and Canterbury blocks exhibits significant insights regarding heating and cooling load. Avalon block in DQLS v2.0 exhibits a heating load of 65-70 (kWh/m2) and 75 -80 (kWh/m2) in the southern region. Whereas CIBSE and ASHRAE 62.1 depict ~ 53 (kWh/m2) in the northern region and 50 -75(kWh/m2) in the southern region. While EN15251 and BB99&101 exhibit similar loads in the northern region (~62 (kWh/m2) and 55 -70 (kWh/m2) in the southern region. In Canterbury, DQLS v2.0

performed slightly better than the Avalon block (~60 (kWh/m2) in the northern region and 70 - 75(kWh/m2) in the southern region. ASHRAE 62.1 exhibits similar heating to Avalon block (~52 (kWh/m2) in the northern region and 50-63(kWh/m2) in the southern region. CIBSE showed ~55(kWh/m2) in the northern region and 50-70 (kWh/m2) in the southern region. EN-15251 and BB 99& 101 showed similar trends in the northern region (~ 60 (kWh/m2), and in the southern region, EN-15251 performed better than BB 99&101. The heating load performs better in the Canterbury block than in the Avalon block. In AKL & HAM, there is a 10 (kWh/m2) difference between Canterbury and Avalon, whereas in the southern region not much difference; however, in QTN, canterbury shows ~6 (kWh/m2) difference to Avalon.

Cooling load in the Avalon block shows ~ 30 (kWh/m2) in the northern region and ~ 23 (kWh/m2) in the southern region. ASHRAE 62.1 shows a significant difference from DQLS v2.0, exhibiting ~11 (kWh/m^2) in the northern region and ~ 9 (kWh/m^2), while the highest in CHCH with 13 (kWh/m^2). CIBSE shows similar loads to ASHRAE 62.1, slightly higher in both northern (~16 (kWh/m2) and southern regions (~12(kWh/m^2). EN-15251 shows a slightly higher ASHRAE 62.1 and CIBSE both in the northern region (~ 21 (kWh/m2) while in AKL 25 (kWh/m2)) and in the southern region ~ 16 (kWh/m^2) and lowest in QTN 10 (kWh/m^2). BB 99 & 101 showed a similar trend to DQLS v2.0 ~30 (kWh/m2) in the northern region and ~18 (kWh/m2) in the southern region, exceptional in CHCH 26 (kWh/m2), similar to DQLS v2.0. In comparison with the Canterbury block, DQLS v2.0 in the northern region exhibits ~ 20 (kWh/m2) and in the southern region ~15 (kWh/m2), slightly higher in CHCH 21 (kWh/m^2). ASHRAE 62.1 showed 13 (kWh/m^2) in the northern region and ~ 12 (kWh/m^2) in the southern region, and CHCH with a slightly higher 18 (kWh/m^2). CIBSE showed ~ 13 (kWh/m^2) in the northern region, similar to ASHRAE 62.1, while in the southern region, varied result with WELL 16 (kWh/m^2), CHCH 18(kWh/m^2) and QTN 12 (kWh/m^2) similar to ASHRAE 62.1. EN15251 ~ 20 (kWh/m^2) in the northern region and ~ 14 (kWh/m2) in the southern region. BB

99 & 101 showed slight similarity to DQLS v2.0 in the northern region ~ 20 (kWh/m2) and in the southern region ~14 (kWh/m^2) while in CHCH 25 (kWh/m^2). In cooling load, Canterbury comparison to Avalon block DQLS v2.0 shows ~ 8 (kWh/m^2) in northern region difference and southern region ~ 9 (kWh/m^2) in WELL and QTN, while only 4 (kWh/m^2) in CHCH.

7.2.1.3 Carbon Dioxide Analysis

The comparative analysis of carbon dioxide significantly shows valuable outputs regarding the Avalon and Canterbury block against DQLS v2.0 and international standards. The Avalon block with DQLS v2.0 showed a ~ 9% spike at 800 ppm at 12 l/s/p baselines, ~ 10 % at 1200 ppm at 7.5 l/s/p and ~ 10.5 % at 2000 ppm at 4 l/s/p across all six climate zones, in contrast, Canterbury shows ~ 4 % spike at 800 ppm at 12 l/s/p, ~4.5 % at 1200 ppm at 7.5 l/s/p and ~3-5% spike at 2000 ppm at 4 l/s/p with exceptional lowered value in WELL ~ 2.5 % spike. Compared to international standards, ASHRAE 62.1 in Avalon shows a ~9 % spike at 1000 ppm at 7.5 l/s/p and in Canterbury, it shows a ~7% spike at the same baseline across all six climate zones. CIBSE shows Avalon with a ~ 6 % spike at 800 ppm at 10 l/s/p, and in Canterbury, it shows a ~ 3.5 % spike at the same baseline across all climate zones. EN15251 shows varied results in Avalon with a ~ 10 % spike in (HAM, QTN and ROTO) and a ~ 6.5 % spike in (AKL, WELL and CHCH) at 800 ppm at 8 l/s/p, while in Canterbury block, EN-15251 shows ~ 6 % spike across climate zone at same baseline in Avalon block. BB 99& 101 shows a ~ 5 % spike in Avalon block at 1500 ppm at 10 l/s/p, and Canterbury depicts a ~ 3.5 % spike at the same baseline value across all climate zones. The comparative analysis of DQLS v2.0 and international standards in both Avalon and Canterbury Block shows a similar trend. Canterbury block exhibits better performance with carbon dioxide concentration.

7.2.1.4 Optimal design changes and simulation findings

This study aimed to develop the optimal post-COVID IAQ and TC design guidelines toward best practices for both the Avalon and Canterbury blocks. Following the critical document analysis and simulations conducted, the following modifications were modelled: *Ceiling height was increased by ~ 1m, and windows vertically adjusted by 0.3m, WWR set to 25 %, R-value in CZ5 (CHCH) were improved by 3.3 % (roof), 6.5 % (wall), 4 % (floor) and CZ6 (QTN) 7 % (roof), 9 % (wall) and 3.8 % (floor) and Clo value from Constant value of 0.75 was improved to 0.8. windows conditioning was set to 12 minutes every 90-120 minutes.* Following the changes, significant changes were observed in both Avalon and Canterbury blocks across all multicriteria for IAQ and TC assessed against international standards. In the Avalon block, the TCP value for DQLS v2.0 in the northern region was improved by ~ 5%, and in the southern region, by ~10% and CSP in the northern region by ~ 5% improvement and in the southern region by ~ 7% in overall (adaptive thermal conditions). In the Canterbury block, which slightly performed lower than Avalon in thermal conditions, the TCP in the northern region improved by 5 % in AKL and HAM while 12 % in ROTO and the southern region by ~ 15 %. The HSP value observed shows improvement by ~ 20 % in managing cold stress across all six climate zones, and CSP improved by ~ 18 % in all six climate zones, significantly in CZ5, minimising overheating issues.

The DA in Avalon block in DQLS v2.0 in the northern region showed 1% improvement, whereas in the southern region, in WELL ~ 2%, CHCH and QTN ~1%. Canterbury block DA in the northern region improved by ~2% in AKL and ROTO, with no changes in HAM, while in the southern region, distinct result with ~1% (WELL), ~6% in CHCH and QTN ~3%. The UDI in the Avalon block for DQLS v2.0 in the northern region showed ~2 % (AKL), ~1% (ROTO) and no changes in HAM, while the Canterbury block showed ~6% in (AKL and HAM) and ~1 % in ROTO, southern region ~ 2 % in (WELL & QTN) and ~6% in CHCH.

The energy analysis showed the Avalon block achieved a ~ 6 (kWh/m^2) reduction in heating load in the northern region and a ~ 15 (kWh/m2) reduction in the southern region. Conversely, the cooling load shows ~ 9 (kWh/m^2) in AKL and HAM reduction in cooling load and 4 (kWh/m^2) in ROTO, while in the southern region, ~ 12 (kWh/m^2) reduction in cooling load. However, in Canterbury, the heating load in the northern region was reduced by 8 (kWh/m^2) and in the southern region by ~ 5 (kWh/m^2) in CHCH and QTN.

The CO2 concentration in the Avalon and Canterbury blocks improved by 35 – 40%. At (Avalon) baseline value, the spike from 10 % dropped to 5.5 %, and in Canterbury, from 3.5 % dropped to ~ 1 % spike.

Significant improvements were achieved for an optimal IAQ and TC post-COVID classroom design.

7.2.3 Validation of (IAQ and TC) best practices

Validation of results and findings is crucial for building performance assessment research. The explanation of the validation methodology and analysis (Objective 4) is depicted in Chapter 6 (see section 6.3). The validation process employed both qualitative and quantitative research methods. Construct validity is established by measuring the underlying construct for IAQ and thermal comfort in an indoor classroom environment. The measurement constructs in this study are IAQ and TC parameters, which were identified through a literature review. Internal validity is established through comparison of DQLS Version 2.0 with established international standards (ASHRAE 62.1, CIBSE, EN-15251, Building Bulletin 99 & 101), the simulation methodology (tools or software) and parametric modelling approach and identify the potential IAQ and Thermal comfort influencing parameters relationship with the indoor environment. External validity is established through industry experts' assessment of the practicality and effectiveness of proposed design modifications. The three validity dimensions use a mixed-method approach. To validate the developed optimal design solution for IAQ and TC best practices for New Zealand primary school classrooms.

7.2.3.1 Appropriateness of Simulation Methodology

The experts used “robust”, “technical”, and “appropriate”, suggesting both “comprehensive” and “valid” with context to the simulation methodology adopted, including software selection based on significant parameters chosen for this study in section 6.3.1.1 in Chapter 6 based on the open-ended questions using thematic analysis. On summarising all ten experts' points of view, a clear divide between technical merit and practical implication was observed. Expert 1- raised the comment with realistic result evidence with simulation results, Experts 3 and 4 raised the concern with the complexity of GH tools with implementation, Expert 5 raised a similar comment to Expert 1 with real building data simulation and its application with cost-effective measure. Expert 6 mentioned a reasonable approach, while Expert 7 found challenges with its more complex modern learning spaces; Expert 8 and Expert 2 noted the parametric modelling approach as robust and quite technical to provide such detailed findings. Expert 9 considers it a well-structured approach considering the maximum impacting environmental parameters. At the same time, Expert 10 highlighted its technical approach but suggested considering different occupancy schedules except for fixed occupancy schedules.

Looking at collective expert feedback on simulation methodology, a general consensus emerges that your approach is technically appropriate for the study parameters, but it requires certain practical considerations to address. These include grasshopper tools complexity, comparison with real-world data simultaneously, adaptability to modern, flexible learning spaces and variable occupancy patterns. Overall, the experts evaluated the simulation methodology has strong technical constructs but would benefit from addressing these practical implementation considerations to maximise its relevance and usability for real-world applications in New Zealand's primary school classrooms.

7.2.3.2 Value of Comparing DQLS (2.0) with International Standards

In evaluating the value of international standard comparisons for DQLS 2.0, experts employed terms like "essential", "valuable", and "critical", indicating both "significance" and "necessity", which is explained in section 6.3.1.2 in Chapter 6 based on an open-ended questionnaire using thematic analysis. Expert 1 identifies the area of improvement for DQLS v2.0, Expert 2 stated that clear comparison within international standards finds potential changes and discrepancies, Expert 3 highlights the need for improvement as per international guidelines to strengthen the local standard, Expert 4 highlights the notion for well tested international standard can help DQLS v2.0, Expert 5 states adapting best practices to NZ guidelines as per climatic conditions, Expert 6 importance of international benchmarking, Expert 7 highlighted that some international standards were not accepted in DQLS v2.0 due to financial constraints, Expert 8 states very highly comparable for preparedness with post-COVID-19 and future pandemic’s, Expert 9 states could benefit NZ approach with school designing form international point of view and Expert 10 highlights the comparison with its effectiveness toward DQLS v2.0.

The predominant experts' perspective supports the comparative analysis of DQLS v2.0 with international standards set by OECD countries, enabling the identification of the discrepancies and potential improvements. Experts believe that proven international standards can significantly strengthen New Zealand's guidelines by adapting best practices to diverse climatic conditions. Feedback indicates that financial constraints have prevented the adoption of some international standards in the current New Zealand framework, signifying that economic factors are vital for making implementation decisions beyond technical considerations. Experts particularly value the comparative approach for post-covid 19 scenarios in schools. Overall, they endorse using international benchmarks to enhance DQLS v2.0 while ensuring adaptations suit New Zealand's unique needs and constraints.

7.2.3.3 Impact of Proposed Design Changes in Classrooms

The experts provided varied perspectives on the design modifications explained in section 6.3.1.3 in Chapter 6. The summary is derived from an open-ended questionnaire discussion and analysed using thematic analysis. Expert 1 endorses ~ 1m ceiling height with better airflow but raises caution about window placement 0.3 vertically due to improper solar and glare assessment while supporting R-value improvement with CZ5 and CZ6. Expert 2 views optimal modification with a balanced perspective, stating ceiling height increase by ~ 1 m creates more volume and better airflow, appreciated windows placement as additional dual daylight and ventilation benefits, raises concerns with heat transfer and implication of R-value and Clo changes. Expert 3 values improved ceiling height and window placement with more space in volume terms, creating a stack effect, emphasising the R-value change in the southern region and stating synergistic benefits of combined modification. Expert 4 believes improved performance is possible without higher costs (except height changes), emphasizes how height increase improves stack effect and creates thermal buffers, supports window adjustments with glare control, and advocates clear communication about clothing policies. Expert 5 states ceiling height appears effective with natural ventilation, but window adjustment should consider glare and solar gain analysis in parallel; improvement with R-value is well calibrated but will incur certain additional construction costs with high insulation application, while Clo acknowledged benefits but cautioned about relying on human behaviour for elements like clothing choices. Expert 6 suggests height increase could improve air circulation by 20-25% but increase costs by 10%, views window adjustments as subtle yet effective, and notes that R-value improvements could significantly reduce heating demands but face humidity challenges.

Expert 7 describes improvements as an "optimal design strategy," suggests investigating additional strategies like external blinds, acknowledges positive impacts on air circulation but notes refurbishment costs, and raises concerns about children's acceptability of clothing recommendations. Expert 8 sees potential with optimal changes, states that height increase enhances stack effect ventilation properties, considers window optimisation with ventilation properties, and says that R-value in the southern region is essential and praises it as a holistic solution. Expert 9 identifies the complex building physics approach, values increased ceiling height for better airflow, notes seasonal impacts of window placement, and emphasizes clothing changes depending on school administration but offers limited R-value assessment. Expert 10 sees changes as viable options, height increase for air stratification and more volume, emphasises window effectiveness depends on glare/solar control, acknowledges thermal performance benefits of R-value improvements while noting cost implications, and appreciates clothing adjustment as practical for New Zealand's varied climate.

The expert's general consensus regarding the changes in proposed design elements received some nuanced consideration. The ceiling height increased by ~1 m, recognised for improvising the airflow and creating healthier ventilation through the stack effect, but significant cost implications are noted. Placing the window position 0.3m vertically overall received mixed feedback and appreciation for dual light and adequate aeration. Still, major concerns were raised for evaluating the discomfort due to glare and solar gain issues. Experts acknowledged the improvement with R-values in CZ5 and CZ6 (southern region) with the thermally balanced conditions but expressed common concern about the cost implications of implementing the additional insulation, which might require a more in-depth holistic analysis. Clothing adjustments were viewed as a practical approach for varied climatic conditions present in New Zealand, but its implementation relies upon human behaviour and school administration programs. Overall, the experts viewed the proposed design changes as a viable solution offering synergetic benefits. However, emphasis should be placed on enactment that offers performance improvements against cost-effectiveness solutions.

7.2.3.4 Optimal IAQ and TC findings (Likert scale Assessment)

The Likert scale assessment conducted with 10 experts from Table 6.2 in Chapter 6 strongly endorsed the proposed methodology and findings for optimal indoor air quality (IAQ) and thermal comfort (TC) guidelines in primary schools using mean score analysis. Expert evaluations across all categories consistently ranged between 3.5 and 4.2 on the 5-point scale, indicating general agreement to strong agreement with the proposed approaches. Adaptive thermal comfort assessment variables received particularly high scores, with TCP and CSP rated at 4.2, closely followed by HSP at 4.1, demonstrating expert confidence in these thermal comfort parameters, which also states the Experts support the new improvement with DQLS v2.0 R-value. However, challenges in the southern region require additional enhancement via optimal design solutions to manage the cold stress. Among the energy analyses, the infiltration load received the lowest score (3.5), though still above the neutral threshold, and the heating and cooling load received (3.7). For indoor air quality assessment, CO_2 concentration by international standards was most strongly supported (4.1), with overall CO_2 and ventilation rate receiving slightly lower endorsement (3.7) and CO_2 concentration value achieved across all six climate zones attained (3.8), due to the high occupancy. Within the proposed optimal design parameters, the R-value for building envelopes (CZ5 and CZ61) scored highest (4.1), while classroom height and clothing insulation received more moderate support (3.9 and 3.7, respectively). While window vertically placement and minimising the WWR 25% attained (4.0). Collectively, these expert ratings validate the robustness of the study's methodology and affirm the practical applicability of the recommended guidelines for improving primary school-built environments.

7.2.4 Critical Interpretation of Findings

The findings reveal three critical insights that extend beyond technical parameters. First, though DQLS V2.0 has strictly considered the CO_2 Concentration to align with international standards, which represent a significant potential change in guidelines. However, the simulation findings revealed a 20-30% divergence in CO_2 concentration among the current school typologies. This difference between actual simulation findings and permissible CO_2 Concentration represents a significant numerical difference between NZ to international standards. Through optimal design modification, an improvement of between 25% and 30% was achieved, demonstrating that classroom typologies require a holistic change, along with strict guidelines that closely align with the international standard, in terms of CO_2. This divergence is particularly concerning for airborne pathogen transmission in New Zealand's educational context, where 25% of children live with asthma and education professionals experienced the highest COVID-19 infection rate (41%) among all occupational groups during the pandemic peak. Maintaining CO_2 levels closer to international benchmarks is not merely a technical specification but a public health imperative that directly addresses these vulnerabilities.

Second, the regional performance disparities between the Canterbury Block and the Avalon Block for climate zones 5 and 6. The thermal comfort showed a 5-12% difference, and the energy analysis ranged between 5 and 10 kWh/m². Hence, this difference in performance reveals that addressing New Zealand's climatic diversity, the DQLS V2.0 requires enhancing the R-Value for the above climate zones. The southern regions (CZ5, CZ6) performed well, with enhanced insulation, indicating where improvements would make the biggest difference. While better insulation costs money to install, this creates an opportunity for the Ministry of Education to plan upgrades in stages rather than all at once. Schools could be prioritised based on which buildings are in the worst condition, which students are most vulnerable to cold and poor air quality, and when buildings are already scheduled for maintenance work. This finding helps identify a clear path for gradually improving standards as budgets allow and priorities are set.

Third, the study reveals that New Zealand schools rely heavily on teachers to open windows, particularly 90% of our schools utilise natural ventilation rather than mechanical systems. Past research shows that less than half of teachers actually open windows during class time, which means that even perfectly designed classrooms can fail to maintain good air quality if the windows remain closed. This highlights a fundamental problem: building better classrooms isn't enough on its own. Actual improvement requires holistic trials, i.e., training teachers on when to open windows, installing sensors to alert them when air quality is poor, and creating clear school policies that make ventilation management part of the everyday classroom routine, rather than an optional extra that teachers might forget during busy teaching moments.

7.3 Recommendations

In light of all the findings of this study (Chapters 1 to 6,) the following recommendations are made:

Design and infrastructure adjustments: Increasing the ceiling height above 3m can help alleviate stagnant zones in classrooms, enhancing air stratification and ultimately improving the efficacy of natural ventilation. Windows placed vertically above can leverage the stack effect, allowing warm air to escape through the upper clerestory openings and pulling more fresh air (Bhagat et al., 2020; WHO, 2021b).

Occupant Density: Minimising the occupant density to 1 child per 2.5 m^2 can allow significant distancing and reduce the aerosol contamination risk and viral infections.

Thermal Conditions: keeping the ideal temperature range between 21℃-23℃ and relative humidity at 40-65% will provide a more thermally comfortable environment and reduce the survival of viral bacteria (REHVA, 2020).

Ventilation Effectiveness and Window Operations: Windows should be fully open during breaks and partially during class (≥ 15 cm gap) to maintain airflow. *Window operation in cold weather*: Windows should be opened for 15 minutes every hour to balance ventilation and thermal comfort (ECDC, 2020; REHVA, 2020). The emphasis on increasing the ventilation rate ensures good indoor ventilation in a post-pandemic scenario to reduce airborne pathogen transmission. Mechanical fans should be used to boost the airflow within the classroom during low wind conditions. The fans that push the airflow should target the air upward to prevent the dispersion of aerial settling aerosols in the classroom (ECDC, 2020; REHVA, 2020).

Ventilation Type and Carbon Dioxide Level: Cross ventilation should be employed to target CO_2 levels below < 800 ppm (WHO, 2021b). High ventilation efficacy should be prioritised through hourly window operations to achieve CO_2 below < 800 ppm (REHVA, 2020). A ~ 6 ACH should be targeted in a naturally ventilated classroom to attain CO_2 below < 1000 ppm. mechanical fans should be considered if poorly ventilated (CIBSE, 2021). CO2 should be around 1000 ppm with 5 ACH, and trickle vents should be used in cold season (ASHRAE, 2021). A continuous airflow (during occupied hours) should be ensured in natural ventilation. Windows should be opened every 15 minutes (hourly) to attain CO_2 below < 1000 ppm (ECDC, 2020).

In the light of post-COVID-19 classrooms, achieving proper indoor air quality and thermal comfort doesn't depend upon a design alone. It requires active occupants' daily practices to ensure holistic improvements via both means optimal design and facilities practices. Below are some recommended actions to ensure that a healthy indoor environment is maintained in classrooms.

Hygiene Protocols: Mandatory instructions to wash hands (20 seconds) with alcohol-based sanitisers before entering school premises and after the meal break reduces transmission of respiratory and gastrointestinal pathogens by 16–23% (CDC, 2023). Educating children with sneezing and coughing in the elbows to minimise the aerial droplets by 50%, disposing of tissues in the classrooms and avoiding facial touches and installing touchless water dispensers (WHO, 2021b).

Facilities Management: Teachers and other staff members should maintain clear directions for opening the windows during operational hours and full during the early morning and break time to clear out the stagnant air in the classroom with fresh air rotation (REHVA, 2020; WHO, 2021b). Caretakers, teachers, and staff members should have the educational directions to monitor CO2 and other pollutants displays and adjust the window's operation according to IAQ requirements. Teachers should also direct basic airflow to children (cold air sinks and warm air rises) (WHO, 2021b; World Health Organization, 2021a). School authorities should directly mandate requirements for healthy IAQ and follow infection prevention frameworks (WHO, 2021b).

Tools Implementation: School authorities must allocate budgets for installing IAQ and Pollutant measuring sensors for regular checkups to identify poor ventilation. Teach teachers and staff to interpret the reading in the sensors and adjust the window opening mechanism based on climatic conditions (Ackley, 2021).

Mental Health Support: Teachers and other caretakers on school premises should be able to recognise the early signs of anxious feelings, withdrawal, and irritability in children. In the post-pandemic environment, 25% of children worldwide experience anxiety, depression and loneliness feeling. Teachers should practice square breathing habits to calm down the anxiousness and practice more engaging activities (UNESCO, 2021).

Physical Health Support: Mandatory physical involvement activities for 60 minutes daily help in improving cognitive functioning and immune systems (UNESCO, 2021).

7.3.1 Implementation Impacts: Health, Policy, and Standards Enhancement

Short-term Impact: The immediate priorities for New Zealand educational facilities focus on three interconnected actions: installing CO_2 monitoring equipment, training teachers on ventilation protocols, and incorporating optimal design features in new buildings. While DQLS v2.0 sets appropriate CO_2 standards aligned with international benchmarks, achieving these levels in practice requires the use of monitoring equipment and consistent window operation. Sensors provide real-time feedback, allowing teachers to know when to open windows and address inadequate ventilation during lessons. The simulation findings show that while both classroom typologies struggle to maintain target CO_2 levels, Canterbury block performs slightly better than Avalon block, demonstrating that building design influences achievable outcomes. Simple protocols, such as keeping windows fully open during breaks and partially open during class, as well as 15-minute hourly openings to every 90 minutes in cold weather, can be integrated into professional development within 12-18 months. Combined with hand hygiene practices, these interventions reduce the transmission of respiratory illnesses, student absences, and improve cognitive ability in the first year. New school projects or retrofit projects (40-60 annually in New Zealand) should incorporate ceiling heights above 3 meters, elevated windows, and 25% window-to-wall ratios at minimal cost during the design phase, creating a foundation for sustained improvement in thermal comfort and indoor air quality standards.

Long-term Impacts: Over the longer term, systematic implementation creates meaningful changes in New Zealand's educational infrastructure, student health, and building standards. A phased retrofit program targeting existing buildings, particularly in colder southern regions such as Christchurch and Queenstown, would implement enhanced insulation and increased ceiling heights during scheduled maintenance cycles, thereby reducing heating demands while improving thermal comfort and air quality. Revising occupancy density standards from the current 2.3 m^2/student toward 3.0-4.0 m^2/student requires additional classroom space but addresses fundamental overcrowding issues that make achieving healthy CO_2 levels difficult, regardless of ventilation efforts, while also reducing viral transmission risks. The accumulated benefits include improved student attendance, better learning conditions, and reduced respiratory illness burden, though the full extent of these gains depends on implementation consistency across diverse school contexts. These design principles also create a climate adaptation framework, enabling buildings to respond as northern regions gradually shift from heating to cooling priorities over the coming decades, while pandemic-ready infrastructure provides ongoing preparedness for future health challenges. Implementing these recommendations positions New Zealand's school design standards for international recognition, establishing regional leadership that can inform similar temperate climates in Pacific Island nations and potentially influencing broader building standards across residential and commercial sectors, with universal indoor air quality monitoring becoming standard practice in an evidence-based building management culture.

7.4 Limitations

Like other scientific research, this study possesses a various limitation which deserves thoughtful consideration from the readers' point of view; the limitations are categorised into four points:

The first limitation relates to the source of data for this study. The original research plan during the confirmation process of this study in late 2020 entailed the case study from Auckland region primary school classrooms to collect real-world data from classrooms and teachers. However, due to safety protocols and the closure of the schools, it became no longer feasible to collect the data. Later after, post-COVID-19 safety protocols and limiting public visits to school spaces prevented the collection of empirical data and connecting with class teachers as initially planned. This constraint led to a thorough review of the initial stages and led to a more comprehensive theoretical framework through an extensive literature review of scholarly articles and conducting document analysis and content analysis. By integrating the local and international standards via the OECD perspective, the study established a grounding body of knowledge that may have broader applicability with site-specific empirical data alone.

This limitation of empirical data led to the modification of the methodology approach to the study. In its place, a simulation methodology using parametric modelling of New Zealand primary schools in six climate zones major cities was adopted. In addition, local and international available standards and guidelines were simulated in New Zealand school classrooms using the Avalon and Canterbury blocks to ascertain the performance of DQLS v2.0 against international standards -ASHRAE 62.1, CIBSE, EN15251, BB 99&101. This alternative route provided a comparative analysis against local and international standards from OECD countries and a credible background for the design of an optimal post-COVID classroom design.

The second limitation concerned with the simulation software used for data visualisation. The selected simulation software (Rhino 7) is regarded as one of the best solutions for parametric modelling and meets all the necessary requirements for assessing the current Indoor Air Quality (IAQ) and Thermal Comfort (TC) in New Zealand school classrooms in accordance with both local and international standards. However, this software does not fully intuitive certain features, such as the holistic comparability of different parameters. The effectiveness of Rhino 7 heavily depends on external plugin tools like Grasshopper, Ladybug, Honeybee, and Energy Plus to perform advanced simulations related to thermal comfort, energy analysis, and airflow. To visualise the data in an intuitive manner and gain a comprehensive view of various parameters, these additional tools are essential. The RHINO 7 software needs another layer of script writing with Python or machine learning, which adds a certain complexity. In performing a simulation, the native software (Rhino 7) along with its plugins, exhibits methodological innovation and technical proficiency.

The third limitation relates to the parameters examined. This study is limited to the primary affecting parameters of IAQ and TC, which directly influence the health, well-being and academic performance of children. The parameters include temp, relative humidity, ventilation rate, carbon dioxide, WWR%, occupancy, occupant density, thermal values for (roof, wall, ceiling, and floor) and carbon dioxide. The other harmful parameters, such as VOCs, carbon monoxide, smoke, pollution, particulate matter and mould, were excluded from this study. This targeted approach allows for a deeper analysis of the primary impacting parameters rather than a surface-level examination of numerous variables. By prioritising the above parameters, this study provided practical relevance to the design perspective and its application to educational facility design and management.

The fourth limitation focuses on the validation procedure. While it was possible to recruit the right academic and industry expertise for this study area, engaging more experts was difficult due to the limited experience of NZ designers who have worked with school classroom designs. Although numerous emails and invitations to participate were sent to individual designers and shared on social media platforms such as LinkedIn, we also contacted designers via professional bodies such as the New Zealand Institute of Architects (NZIA), the New Zealand Chartered Institute of Building (NZIOB), etc. It would have been good to get more than the 10 experts. However, the quality of the expert's feedback provided significant insights that might be a bit contradicting from a much larger sample size. This focused validation approach ensured that feedback came from individuals with the most relevant expertise, enhancing the credibility of the validation process.

The fifth limitation focuses on the generalisability considerations. While this study offers robust insights for New Zealand primary school classrooms, several factors limit its generalizability. The two classroom blocks (Avalon and Canterbury) represent common architectural typologies in NZ, but do not capture the full diversity of educational building stock. The six climate zones studied encompass New Zealand's major population centres but overlook microclimatic variations—coastal versus inland locations within the same climate zone can exhibit different ventilation effectiveness due to prevailing wind patterns.

The study's focus on natural ventilation (representative of 90% of NZ schools) means findings have limited applicability to mechanically ventilated or hybrid systems. Results may not be applicable to intermediate and secondary schools, where occupancy patterns, space utilisation, and occupant behaviours differ substantially from those in primary settings. Internationally, the findings hold relevance for temperate maritime climates (OECD Countries) but require careful adaptation for continental, tropical, or arctic educational contexts. The

Experts' assessment validates the simulation-based methodology; the findings could be more robust when verified through occupied classroom monitoring. This study establishes theoretical potential; translating that potential into realised outcomes requires implementation studies with post-occupancy evaluation. The generalizability of findings should therefore be understood as provisional, subject to confirmation through field-based research across diverse school contexts.

7.5 Future Research

Besides achieving the study aim, certain important avenues for future research emerged to improve the state of IAQ and TC in school building classrooms in New Zealand.

Beginning with the first limitation of empirical data collection, the study calls for future research that could benefit from collecting real-time IAQ and TC data, as well as obtaining teachers' opinions and perceptions of school classroom performance, as an essential extension to this simulation-based work. Understanding what teachers and students actually experience on a daily basis would validate or challenge the simulation findings and reveal practical implementation issues that computer models cannot predict. Future research should also examine how indoor environmental quality varies across different school communities and incorporate cultural perspectives, particularly Māori concepts of environmental well-being, into design frameworks. It would be interesting to examine behavioural changes due to the discomfort experienced. Also, future research can look into the post-occupancy evaluation of classrooms to better understand physical environmental conditions, psychological and social well-being, and academic outcomes in relation to sustainable design features. Research focused on how people use classrooms can help correlate these findings with adaptive learning design concepts.

The study utilises one of the latest software packages to conduct parametric simulation, which serves as a best-fit tool to simulate all the necessary parameters directly associated with IAQ and TC in school classrooms. However, its limitations with data visualisation call for future research that could integrate with advanced script writing tools such as Python and machine learning to holistically show the influence of one parameter on the other. Another additional tool, such as the Octopus plugin, could be used with Energy Plus to perform a Pareto analysis for multiple domain optimisation (IEQ parameter), providing a clearer understanding of the influencing parameters on one another.

Future research can also investigate the impact of solar gain and building orientation on indoor environmental quality parameters in primary school classrooms. Though this study considered different WWR% across numerous simulation strategies, shade and façade, solar gain and building orientation can significantly influence visual and thermal comfort. Researchers can better understand how architectural configuration influences thermal comfort, energy efficiency, and learning environments by systematically analysing facade designs and strategies across multiple orientations in significant climate zones.

This research acknowledges the primary parameters associated directly with inadequate indoor air quality and thermal discomfort in school classrooms, impacting children's health and well-being, academic outcomes and absenteeism. Future research can also look into other environmental pollutants that trigger an unhealthy indoor environment, such as volatile organic compounds (VOCs), particulate matter ($PM_{2.5}$), carbon monoxide (CO), pollution and mould.

Collectively evaluating the IEQ in school classrooms requires a holistic assessment of all four parameters (indoor air quality, thermal comfort, visual comfort and acoustics). Hence, future research can expand the evaluation of visual comfort and acoustics and correlate with the findings of IAQ and TC from this study to make a holistic analysis of IEQ's impact on school classrooms. Additionally, the dynamic occupancy schedule and operational schedule can also be considered to explore both physical and behavioural interventions to create a framework for IEQ enhancement.

Future research can also look into the cost analysis of design modification, predictive modelling for climate change and its impact on IEQ parameters. This collective predictive technique would extend beyond parametric modelling to include extensive field testing across diverse climate zones, specifically focusing on understanding how climate change might alter indoor environmental requirements in school environments. Economic analysis comparing retrofit costs against health and attendance benefits would help policymakers make informed decisions about prioritising improvements across the school building stock.

The research directions outlined above collectively emphasise a fundamental principle: improving educational environments requires sustained, multifaceted investigation rather than isolated studies. This study presents significant insights into the importance of IAQ and TC in school environments and their impact on children's health, well-being, and educational outcomes in New Zealand, while also revealing areas for future improvement. The complexity of classroom environments encompassing physical, biological, psychological, and social dimensions demands collaborative research programs that bring together building scientists, health researchers, educators, architects, and, critically, students themselves. Following the recommendation, limitations, and future research descriptions, strengthening relationships between varied factors can support a more nuanced framework for developing a more comfortable and sustainable learning environment. Moreover, integrating the simulation expertise with the real-world monitoring, occupant feedback, economic analysis, and diverse school contexts will build a robust evidence base for designing healthier schools not just in New Zealand, but in similar contexts globally.

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Appendices

Appendix 1

Validation Consent Form

A New Normal for Classroom of Primary School- Post Covid 19: A Case Study New Zealand

STATEMENT OF CONSENT

By signing this statement, I give permission to the researcher to include my responses in the focused group interview on Indoor Air Quality (IAQ) and Thermal Comfort in primary school classrooms. I understand this study aims to gather expert opinions and insights on IAQ and Thermal Comfort design in classrooms. The data collected will be used for research purposes and to inform future improvements in classroom design and environmental conditions to help with children's health and well-being, productivity and performance, teachers and other co-workers.

I have read the information sheet provided, and any questions asked have been answered satisfactorily. I understand that the data I provided will be kept confidential and that I will not be identified in any publications of findings from this research without my explicit permission. I also understand that I may ask further questions at any time, and I have voluntarily full right to withdraw from this study without providing a reason.

Signature: .... **Date:** ....

Full Name ....

Appendix 2

Validation Participant Information Form

A New Normal for Classroom of Primary School- Post Covid 19: A Case Study New Zealand

Participant Information Sheet

Dear participant,

Thank you for your interest in participating in this focus group validation process for this study. The purpose of this process is to critique and ascertain the science and review approach taken to achieve the study aim.

You have been selected as an academic expert in a research area that is integral for this PhD study. Before you proceed, we would like to provide you with important information about the study and your participation.

Study Aim:

This study aims to develop an Indoor Air Quality (IAQ) and Thermal Comfort (TC) best practice for post–COVID–19 in New Zealand primary school classrooms. The objectives include:

1. **1.** To critically evaluate the DQLS V (2.0) IAQ and TC design guidelines with international guidelines (OECD Countries) for the post-COVID-19 environment for six climate zones in New Zealand.
2. **2.** To ascertain the suitability of current IAQ and Thermal Comfort design guidelines for six climate zones in New Zealand.
3. **3.** To design a post-COVID-19 optimal IAQ and TC design best practice for six climate zones in New Zealand primary school classrooms.
4. **4.** To validate the developed optimal post-COVID-19 IAQ and TC design best practice for six climate zones in New Zealand primary school classrooms.
5. **5.** To recommend improvement opportunities for Designers and the Ministry of Education (MOE) to achieve healthy primary school classrooms in New Zealand.

In the course of this PhD, we have achieved objectives 1 – 3. This invitation is part of the activities required for objective 4.

Based on your research expertise in the area of building occupant health and wellbeing, you are invited to provide your professional views to this study. Your expert contribution will assist in refining the designed post-COVID-19 IAQ and TC design best practice. It will also provide useful data for achieving objective 5.

Study Procedures:

Participation in this study involves attending a focus group workshop for two hours. This will include a 15 to 20 minutes presentation of the research findings, followed by Q&A session to retrieve your professional opinions. At the end of the session, a brief questionnaire survey will be conducted consisting of multiple-choice and open-ended questions. Refreshments will be provided.

Confidentiality:

Your participation in this study is entirely voluntary and anonymous. Your responses will be kept confidential and stored securely within the Massey University database. Only the researchers and project supervisors involved in the study will have access to the data gathered, and your individual response will not be identifiable in any reports or publications.

Data Protection:

The data collected in this study will be stored securely and following relevant data protection rights and regulations designed by Massey University. Your personal information will be kept confidential, and your responses will be anonymised during data analysis.

Benefits and Risks:

Participating in this study will contribute to our understanding of IAQ and Thermal Comfort within classrooms and may help improve future learning environments. There are no anticipated risks associated with participating in this study.

Voluntary Participation:

Your participation in this study is completely voluntary. You have the right to withdraw from this study at any time without providing a reason. Your decision to participate or not will not affect your current or future relationship neither with Massey University or any other governing entity or school.

Human Ethics:

We have received a low-risk ethics approval**: Ethics Notification Number: 4000027845**

This project has been evaluated by peer review and is considered low-risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher named below in (Contact Information) is responsible for the ethical conduct of this exercise.

If you have any concerns about the conduct of this audit that you wish to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director (Research Ethics), email humanethics@massey.ac.nz

Contact Information:

If you have any questions or concerns regarding the study, you can directly reach out to researchers and the project supervisor's contact details are mentioned below.

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Thank you for your time and your kind support!

Appendix 3

Validation Open-Ended-Close-Ended Questions Form

A New Normal for Classroom of Primary School- Post Covid 19: A Case Study New Zealand

Validation Open-Ended Questions

The questionnaire is designed to validate our study, "A New Normal for Classrooms of Primary School - Post Covid-19: A Case Study New Zealand." It assesses the appropriateness, practicality, and significance of our simulation results on indoor air quality and thermal comfort in New Zealand primary school classrooms. The questionnaire uses four open-ended questions, and other questions are based on a 5-point Likert scale: Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree. This format allows for a nuanced evaluation of our findings on thermal comfort, daylight autonomy, energy loads, and carbon dioxide levels across different climate zones and classroom designs. Your expert responses will provide crucial insights into the validity and relevance of our research for post-COVID-19 classroom environments in New Zealand.

Section 1: General Questions

Q1. How would you evaluate the appropriateness and practicality of the simulation methodology used in this study for assessing classroom environments?

Answer: ………………………………………………………………………………………

Q2. What value do you see in comparing the DQLS version (2.0) with different international standards (ASHRAE 62.1, CIBSE, EN-15251, Building Bulletin 99 & 101) for this study?

Answer:…………………………………………………………………………………………..

………………………………………………………………………………………………….

Q3. What impact do you perceive the proposed classroom design can have (e.g., Increased height, Window placement, WWR, R-value and clothing insulation) on indoor air quality and thermal comfort performance?

Answer:…………………………………………………………………………………..…

…………………………………………………………………………………………………

Q4. What recommendations would you like to propose to achieve a healthier indoor environment in primary school classrooms in New Zealand?

Answer:………………………………………………………………………………………

…………………………………………………………………………………………………

Validation Close-Ended Questions

Section 2: Adaptive Thermal Comfort					
Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The Thermal Comfort Percentage (TCP) values are appropriate for each climate zone.					
The Heating Sensation Percentage (HSP) are appropriate for each climate zone.					
The Cooling Sensation Percentage (CSP) values are appropriate for each climate zone.					
The thermal comfort results for Christchurch and Queenstown adequately represent the challenges of a colder climate.					

Section 3: Energy Loads					
Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The cooling and heating loads are appropriate for each climate zone?					
The infiltration load data are appropriate for each climate zone.					
The Natural Ventilation (NV) loads are appropriate for each climate zone and support the potential for passive cooling strategies.					
Section 4: Carbon Dioxide and Ventilation					
Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The CO_2 concentration across climate zones in both open and closed-design classrooms					

are appropriate conditions for indoor air quality.					
The variations in ventilation rate to CO_2 concentration across are appropriate and encourage a high ventilation rate.					
The achieved CO_2 concentration is in line with international standards.					
The overall CO_2 concentration in both designs and climate zones supports the optimal air quality in the classroom.					
Section 5: Proposed Optimal Design Changes					
Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree

Do you agree that increasing the classroom height by ~1 meter improves thermal comfort and air quality across climate zones?					
Do you agree moving windows upwards by 0.3 cm and improving manual window opening schedule enhances natural ventilation across climate zones.?					
Do you agree adjusting the window-wall ratio optimises indoor air quality and thermal comfort across different climate zones.					
Do you agree that modifying clothing insulation values (clo) can significantly impact classroom thermal comfort					
Do you agree adjusting R-values for roofs, walls, and floors/ceilings achieves optimal					

thermal comfort across different climate zones.					

Appendix 4

Human Ethics Notification

From: humanethics@massey.ac.nz
Sent: Tuesday, 8 August 2023 11:30 pm
To: Vineet Arya; Don Samarasinghe; Eziaku Rasheed; Suzanne Wilkinson
Cc: Human Ethics
Subject: [HE007] - Human Ethics Notification - 4000027845

Kia ora,

Link to the application
HoU Review Group

Ethics Notification Number: 4000027845
Project Title: A New Normal for Classroom of Primary School- Post Covid 19: A Case Study New Zealand

Thank you for your notification which you have assessed as low risk.

Your project has been recorded in our database for inclusion in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

Please notify me if situations subsequently occur which cause you to reconsider your initial ethical analysis that it is safe to proceed without approval by one of the University's Human Ethics Committees.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact the Research Ethics Office, email humanethics@massey.ac.nz."

Please note that if a sponsoring organisation, funding authority or a journal in which you wish to publish require evidence of committee approval (with an approval number), you will have to complete the application form again answering yes to the publication question to provide more information to go before one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

You are reminded that staff researchers and supervisors are fully responsible for ensuring that the information in the low risk notification has met the requirements and guidelines for submission of a low risk notification.

If you wish to print an official copy of this letter:

1. Please login to the RIMS system (https://rme.massey.ac.nz).
2. In the Ethics menu, select Ethics Applications.
3. Using the Advanced option, select Ethics Applications (Area), Application ID (Search On), enter the ethics notification number in the Value area and select Find on the toolbar.
4. With the application the Results Tab, tick the empty box on the far left of the application and select Reports from the toolbar.
5. Select the "Human Ethics - Low Risk Notification Letter" link, this will open the report viewer.
6. Select the application code from the Report Parameters dropdown and submit. You can then select an export option from the top toolbar (Print, Save).

Yours sincerely

Professor Tracy Riley
Acting Chair, Research Ethics Chairs' Committee and Acting Director, Research Ethics

Appendix 5

DRC16 – Statement of Contribution

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Vineet Kumar Arya
Name and title of main supervisor:	Dr. Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	Chapter 3
What percentage of the manuscript/published work was contributed by the student?	80

Describe the contribution that the student has made to the manuscript/published work:
Literature review, Methodology, Data collection and analysis and Original Draft preparation.

Please select one of the following three options:

(●) **The manuscript/published work is published or in press**

Please provide the full reference of the research output:
Arya, V., Rasheed, E. O., Samarasinghe, D., & Wilkinson, S. (2023, November). A Review of Indoor Air Quality and Thermal Comfort Guidelines for New Zealand Primary School Classrooms: A Comparison of DQLS Document (Old Versus New). In International Conference on Engineering, Project, and Production Management

( ) **The manuscript is currently under review for publication**

Please provide the name of the journal:

( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	vineet kumar arya — Digitally signed by vineet kumar arya Date: 2025.04.10 12:31:39 +12'00'	Main supervisor's signature:	Eziaku Rasheed — Digitally signed by Eziaku Rasheed Date: 2025.04.11 13:03:28 +12'00'

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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Student name:	Vineet Kumar Arya
Name and title of main supervisor:	Dr. Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	4
What percentage of the manuscript/published work was contributed by the student?	80

Describe the contribution that the student has made to the manuscript/published work:
Literature review, Methodology, Data collection and analysis and Original Draft preparation.

Please select one of the following three options:

(●) **The manuscript/published work is published or in press**

Please provide the full reference of the research output:

Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S., & Wilkinson, S. (2024). "Comparative Analysis of Indoor Air Quality and Thermal Comfort Standards in School Buildings across New Zealand with Other OECD Countries". Buildings, 14(6), 1556. https://doi.org/10.3390/buildings14061556

( ) **The manuscript is currently under review for publication**

Please provide the name of the journal:

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Student's signature:	vineet kumar arya Digitally signed by vineet kumar arya Date: 2025.04.10 12:42:39 +12'00'	Main supervisor's signature:	Eziaku Rasheed Digitally signed by Eziaku Rasheed Date: 2025.04.11 13:04:00 +12'00'

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Student name:	Vineet Kumar Arya
Name and title of main supervisor:	Dr. Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	5
What percentage of the manuscript/published work was contributed by the student?	80

Describe the contribution that the student has made to the manuscript/published work:
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Please select one of the following three options:

○ **The manuscript/published work is published or in press**

Please provide the full reference of the research output:

◉ **The manuscript is currently under review for publication**

Please provide the name of the journal:

Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S.,(2025). "A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New Zealand's Six Climate Zones (1): The Avalon Typology" (Under-Review – Buildings 3595956)

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Literature Review, Methodology, Data collection and Analysis and Original draft preparations.

Please select one of the following three options:

○ **The manuscript/published work is published or in press**

Please provide the full reference of the research output:

◉ **The manuscript is currently under review for publication**

Please provide the name of the journal:

"Smart and Sustainable Built Environment" from "Emerald Publishing" by Arya, V. K., Rasheed, E. O., Samarasinghe, D. A. S.,(2025). "A Simulation-Based Study of Classroom IAQ and Thermal Comfort Performance Across New Zealand's Six Climate Zones (2): The Canterbury Typology" (SASBE-04-2025-0168).

○ **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	vineet kumar arya Digitally signed by vineet kumar arya Date: 2025.04.10 12:31:39 +12'00'	Main supervisor's signature:	Eziaku Rasheed Digitally signed by Eziaku Rasheed Date: 2025.04.11 13:02:24 +12'00'

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Name and title of main supervisor:	Dr. Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	6
What percentage of the manuscript/published work was contributed by the student?	80

Describe the contribution that the student has made to the manuscript/published work:
Literature Review, Methodology, Data collection and Analysis and Original draft preparations.

Please select one of the following three options:

(●) **The manuscript/published work is published or in press**

Please provide the full reference of the research output:
Arya, V., Rasheed, E. O., & Samarasinghe, D. (2025 February). "Validation of Optimal Indoor Air Quality and Thermal Comfort Design Guidelines for Post-COVID-19 New Zealand Primary School Classrooms". Holistic Living: Sustainable, Affordable, and Resilient Built Environment. (NZBERS)

( ) **The manuscript is currently under review for publication**

Please provide the name of the journal:

( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	vineet kumar arya — Digitally signed by vineet kumar arya Date: 2025.04.10 12:31:39 +12'00'	Main supervisor's signature:	Eziaku Rasheed — Digitally signed by Eziaku Rasheed Date: 2025.04.11 13:02:57 +12'00'

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