PASSIVE VENTILATION AS A THERMAL ADAPTATION STRATEGY FOR SOUTH AFRICAN CITIES IN TEMPERATE CLIMATE REGIONS

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Declaration of originality

I declare that the mini-dissertation, Passive Ventilation as a Thermal Adaptation Strategy for South African Cities in Temperate Climate Regions, which has been submitted in fulfilment of part of the requirements for the module of Design Investigative Treatise (DIT 801), at the University of Pretoria, is my own work and has not previously been submitted by me for any degree at the University of Pretoria or any other tertiary institution.

I declare that I obtained the applicable research ethics approval in order to conduct the research that has been described in this dissertation.

I declare that I have observed the ethical standards required in terms of the University of Pretoria's ethical code for researchers and have followed the policy guidelines for responsible research.

Signature: ……………………………………………………………

Date: 24 - 07 - 2023 ……………………………………………………………

Abstract

In the 21st century, climate change poses a formidable challenge for humanity, with Southern Africa particularly vulnerable due to its geographic location and socioeconomic development (Allan et al., 2021). This region is projected to face even higher temperatures and drier conditions as a consequence of climate change, with a warming rate approximately double the global average (MacKellar, New and Jack, 2014). Buildings and related industry sectors significantly contribute to carbon emissions and urban residents' well-being, necessitating effective strategies to enhance thermal responsiveness and reduce the reliance on artificial cooling. This research report focuses on identifying and analysing effective strategies for enhancing buildings' thermal responsiveness, with a specific emphasis on measures to reduce the need for artificial cooling. The study explores various techniques and technologies promoting natural cooling and energy efficiency in buildings, contributing to the discourse on climate adaptation strategies. Understanding the specific climate classification is crucial, leading to the investigation of technologies implemented in regions with similar climatic conditions as observed in Tshwane, South Africa. The structured report includes chapters on background, methodology, literature review, case studies of passive ventilation strategies for cooling, data analysis, and conclusions. The research findings reveal buoyancy-driven case studies with promising results, incorporating methods for measuring ventilation effectiveness. Case study 3 stands out for its approach of segmentation for ventilation, offering valuable insights for enhancing passive ventilation strategies. The report aims to contribute to climate change adaptation, emphasising effective strategies for enhancing thermal comfort and reducing reliance on artificial cooling in buildings.

Keywords

Climate change Adaptation, Passive Ventilation, Temperate Climate Regions, Wind Driven Ventilation, Buoyancy Driven Ventilation

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1. Introduction

In the expansive realm of the 21st century, humanity faces a formidable obstacle: climate change. The consequences of this worldwide phenomenon are increasingly evident, with each passing decade recording higher temperatures than its predecessor (Allan et al., 2021). Southern Africa is particularly vulnerable to the effects of climate change owing to its geographical location and current level of socioeconomic development. Being situated in a predominantly warm and arid region, the area is projected to face even higher temperatures and drier conditions as a result of climate change. The rate of warming in the interior of southern Africa is approximately double the global average (MacKellar, New and Jack, 2014).

Buildings and related industry sectors contribute 6.4% and 21% of direct and indirect carbon emissions, respectively, impacting urban residents' well-being (Bergamo Dos Santos, 2016). Urbanisation and increasing electricity demand drive these emissions, with anthropogenic activities responsible for up to 75% of greenhouse gases released (Bergamo Dos Santos, 2016). The rising use of air conditioners also intensifies electricity consumption. As global urbanisation continues, there's a growing need for electric cooling measures in buildings (Archdaily,2023).

The primary objective of this research is to identify and analyse effective strategies that enhance the thermal responsiveness of buildings, with a specific focus on measures aimed at reducing the need for artificial cooling. The study aims to explore and evaluate various techniques and technologies that promote natural cooling and improve energy efficiency in buildings. By investigating these strategies, the research aims to make a meaningful contribution to the broader discourse on climate adaptation strategies and sustainable building practices.

Comprehending the specific climate classification is of paramount importance when studying and proposing effective architectural technologies as adaptation strategies for thermal amelioration. As a result, it becomes essential to identify and analyse technologies implemented in regions sharing similar climatic conditions as observed in Tshwane, South Africa. This approach ensures more precise and targeted recommendations to tackle climate challenges and successfully implement adaptation strategies. By focusing on relevant climatic analogues, the research can provide valuable insights into suitable and context-specific solutions for enhancing thermal comfort and resilience in the region.

The report follows a structured format. Chapter 2 provides relevant background information, setting the context for the research. In Chapter 3, the methodology is discussed, with a specific focus on the CMMO method of analysis. This chapter also outlines the research questions, objectives, and limitations. Chapter 4 presents a detailed literature review on climate adaptation strategies, with an emphasis on passive ventilation strategies for cooling. Chapter 5 contains a compilation of case studies employing passive ventilation for cooling. An analysis of outcomes, efficiencies, benefits, and limitations are presented. Chapter 6 involves a comprehensive discussion of the gathered data, while Chapter 7 presents the conclusion.

This report aims to contribute to the pressing challenge of climate change, particularly in vulnerable regions like Southern Africa. It emphasises effective strategies, particularly passive ventilation for cooling, to enhance thermal comfort and alleviate reliance on artificial cooling in the built environment. Through a structured approach, the report seeks to offer valuable insights and recommendations for climate adaptation in building practices.

2. Background

2.1 Climate Change on a Global Scale:

In the vast landscape of the 21st century, one formidable challenge looms over humanity: climate change. The effects of this global phenomenon are steadily becoming more apparent as each passing decade registers higher temperatures than the previous one (Allan et al., 2021). Since the year 1880, the average surface temperature has witnessed an increase of nearly 1 degree Celsius, with the period spanning from 2001 to 2019 etching its name in history as hosting 19 of the warmest years ever recorded (Akkose, Meral Akgul, and Dino, 2021).

Human activities such as deforestation, fossil fuel consumption, and urbanisation have led to the increase in emission of greenhouse gases that trap heat in the atmosphere of the Earth and cause temperatures to rise (Hope, 2009). Human-induced emissions contribute to a range of damaging environmental consequences such as elevated global temperatures, reduced ice sheets, warmer oceans, higher sea levels, severe weather events, and increased ocean acidity (Akkose, Meral Akgul, and Dino, 2021). The Intergovernmental Panel on Climate Change (IPCC) reports that human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels. If such increases continue, global warming is predicted to reach 1.5°C between 2030 and 2052 (Allan et al., 2021).

According to the IPCC (2016), rising temperatures are causing changes in weather patterns, leading to more frequent occurrences of heatwaves, hot extremes, and heavy precipitation. These changes are having adverse effects on both human communities and the environment (Allan et al., 2021). The phenomenon of global warming has emerged as a significant danger to the sustainable development and progress of all regions worldwide, with a particular impact on Africa (Hope, 2009).

In 2015, the Paris Accord was established with the primary goal of limiting the increase in global temperatures to 2°C by the end of the century. The 2015 Accord further aims towards restricting the increase to 1.5°C (Fawzy *et al.*, 2020). Nevertheless, in the absence of emission reduction measures by 2030, projections indicate an inevitable increase in global temperatures by 3°C to 4°C above pre-industrial levels by 2100 (Allan et al., 2021). This rise would be regarded as unavoidable from a geophysical standpoint.

The impacts of climate change are global in scale, but the severity of its effects varies across different regions of the world. Some regions experience more pronounced effects than others.

2.2 Climate Change on a Local Scale:

Southern Africa is highly susceptible to the impacts of climate change due to its geographical location and current level of socioeconomic development. Situated in a mainly warm and arid region, it is anticipated to experience even hotter and drier conditions as a consequence of climate change. The rate of warming in the interior of southern Africa is approximately twice as fast as the global average (MacKellar, New and Jack, 2014).

Human actions and policies will determine the extent of climate change in the 21st century. If the world opts for "low mitigation futures," where warming exceeds 3°C, South Africa's future development is at a higher risk compared to "high mitigation futures," which limit warming below 2°C, or even lower. Immediate and robust efforts are required to reduce greenhouse gas emissions, in developing countries like South Africa. (MacKellar, New and Jack, 2014).

Failure to prioritise climate mitigation measures can lead to anticipated climate-related risks at both global and local levels.

2.3 Global Climate related risks:

The last decade has been the warmest on record, and temperatures are rising rapidly, causing numerous negative impacts. Hotter temperatures lead to more frequent heat waves and sustained wildfires, making it more difficult to work outdoors and leading to heat-related illnesses. Severe storms are becoming more intense and frequent due to climate change, exacerbating extreme rainfall and flooding. Water availability is decreasing, leading to increased drought and dust storms. The warming and rising ocean presents a significant threat to both coastal communities and marine life. As global temperatures continue to rise, the resulting climate change also brings forth a range of adverse effects. These effects include the loss of species, heightened health risks, increased poverty levels, and population displacement (UN, 2020).

The risks associated with climate change are intricately linked to the unique climatic conditions of specific regions worldwide. Each region faces distinct challenges and vulnerabilities due to climate change, influenced by factors such as geography, weather patterns, and existing ecosystems.

2.4 Climate related risks in South Africa:

Agricultural production in South Africa is likely to decrease due to climate change, with staple crops and livestock being affected (MacKellar, New and Jack, 2014). The region is already beyond the optimal temperature for crop and livestock production, and decreased soil moisture will further decrease crop and forage production (MacKellar, New and Jack, 2014). Already limited availability of freshwater will become scarcer as rainfall decreases and evaporation rates increase. Droughts will become more frequent and intense, leading to overwhelmed coping mechanisms (MacKellar, New and Jack, 2014). Heat waves will become more intense, leading to increased human mortality, and decreased outdoor labour capacity. Climate change will also increase the risk of severe storms and premature extinction of species, with negative consequences for human well-being and the economy (MacKellar, New and Jack, 2014).

There is also growing evidence that high temperatures may increase the likelihood of interpersonal violence. South Africa is already a country with high levels of violence and as the climate warms, it may become more vulnerable to this consequence of climate change (Chersich *et al.*, 2019). It is expected that there will be a 4-5% increase in homicides per degree rise in temperature. If the temperature in South Africa rises by 1°C, the number of homicides per year will increase by 800 to 1000 (Chersich *et al.*, 2019). A study conducted in the Tshwane metropolitan area of the Gauteng Province, found that on high-temperature days the number of violent crimes was about 50% higher than on low-temperature days. Another study in the same area found that violence was more common in the summer months (Chersich *et al.*, 2019).

Climate change is caused by a multitude of factors, with the built environment playing a prominent role in driving this global issue. Consequently, it contributes significantly to both global and local climate-related risks..

2.5 The Built environment as a Climate Change driver:

According to Bergamo Dos Santos (2016), buildings and related industry sectors account for 6.4% and 21% of direct and indirect carbon emissions, respectively. These emissions consist of both embodied and operational components, and they can significantly impact the health and well-being of urban residents. Urbanisation and the growing demand for electricity are driving forces behind these emissions, as anthropogenic activities play a major role in climate change by releasing greenhouse gases (GHGs). In fact, up to 75% of GHGs released into the atmosphere are attributed to anthropogenic activities, further emphasising the crucial role that cities must play in addressing and mitigating these emissions (Bergamo Dos Santos, 2016).

Fatih Birol, the Executive Director of the International Energy Agency (IEA), states that the increasing use of air conditioners is a significant blind spot in current discussions on energy. The IEA reports that air conditioning and electric fans account for nearly 20% of total electricity consumption in buildings worldwide. The IEA predicts that by 2050 the number of air conditioning units will triple, consuming as much electricity globally as the current combined energy consumption of India and China. This trend is worrisome considering the lengthening and intensifying heat waves experienced globally (Archdaily,2023).

With the ongoing process of global urbanisation, there is an expected surge in the demand for infrastructure within cities. Consequently, this surge creates a greater necessity for the implementation of electrically-driven cooling measures in buildings.

2.6 Global and Local Urbanisation:

Urbanisation is a global trend in which people move from rural areas to urban centres. The Economist (2012) estimates that by 2050 nearly 64% of the developing world and 86% of the developed world will be urbanised.

Sub-Saharan Africa has seen significant urbanisation growth, particularly in medium-sized cities and those with populations of less than one million (Bergamo Dos Santos, 2016). It is estimated that the population of Gauteng will surge by 8.1 million people by the year 2050, increasing from just over 12 million in 2011 to a total of 20 million inhabitants. Despite being the smallest of South Africa's nine provinces, Gauteng boasts the highest population density. Located within this province are the three most rapidly expanding metropolitan areas; Johannesburg, Pretoria, and Ekurhuleni. By 2050 these metropolitan areas are estimated to grow 84%, 76%, and 60%, respectively. The population of the City of Tshwane Metropolitan Municipality is forecast to expand by 2.2 million individuals by 2050. Meeting the needs of this growing population will require sufficient infrastructure in areas such as housing, commerce, healthcare, and education (CSIR, n.d.).

Rapid urbanisation contributes to the expansion of urban sprawl, leading to denser built-up areas (Zhou and Chen, 2018). This shift in urban morphology is associated with the emergence of the urban heat island (UHI) phenomenon, wherein cities experience notably higher temperatures compared to their rural surroundings (Zhou and Chen, 2018).

Paradoxically, as climate change conditions drive more people towards urban areas, this exacerbates the issue since urbanisation itself contributes to further climate change.

2.6 Urban Heat Island Effect:

The Urban heat island (UHI) contributes to global warming, heat-related mortalities, and unpredictable climatic changes (Deilami, Kamruzzaman and Liu, 2018). First discovered in London in 1818, subsequent research has shown its existence in many countries and regions worldwide.

The Urban Heat Island (UHI) effect is observable in dense urban areas. This effect arises due to distinct characteristics of the urban underlying surface compared to rural areas. The urban surface exhibits high heat capacity and thermal conductivity while predominantly comprising waterproof materials. Furthermore, building surfaces contribute to the expansion of the urban surface area, resulting in multiple reflections and absorption of heat (Zhou and Chen, 2018). As a consequence, this amplifies the absorption and storage of heat flux within urban areas. Urban areas feature numerous high-rise buildings, which contribute to increased surface area roughness. Surface area roughness refers to the unevenness or irregularity of the surfaces present in an environment. In the context of urban areas, it refers to the presence of tall buildings, structures, and other elements that disrupt the smoothness of the urban landscape (Zhou and Chen, 2018).

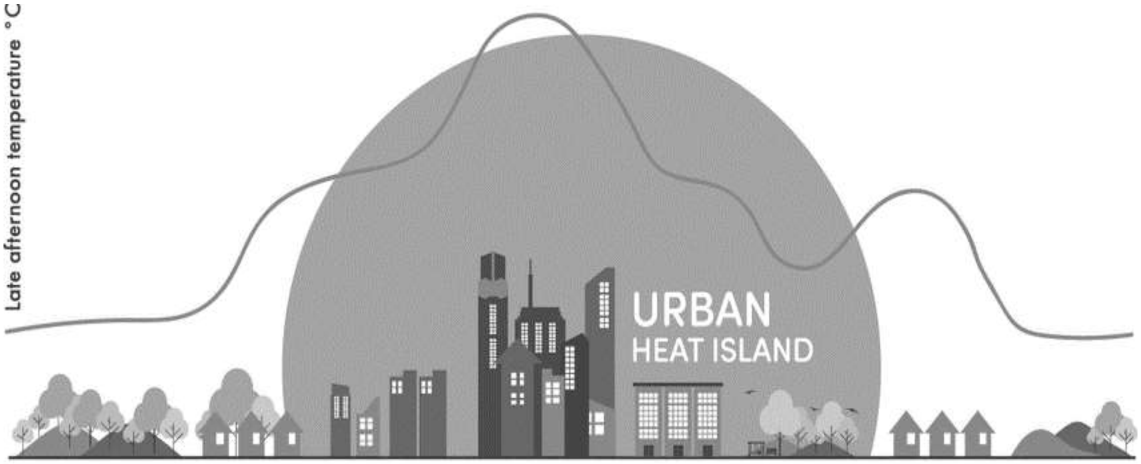


Figure 1 / Urban Heat Island Effect (Zhou and Chen, 2018)

These vertical features create variations in the height and arrangement of surfaces, leading to a more complex and jagged urban morphology. As a result, air flows and wind patterns encounter more obstacles and experience increased turbulence, affecting the ease of ventilation and heat dissipation within the urban environment. As a consequence, a substantial amount of heat becomes trapped and accumulates in wind-sheltered spaces within cities (Zhou and Chen, 2018). Anthropogenic heat also adds to the heat, leading to a greater tendency for urban areas to experience higher outdoor air temperature levels than rural areas (Zhou and Chen, 2018). This rise in temperatures in urban areas leads to increased reliance on artificial cooling sources such as air conditioning, resulting in higher pollutant emissions (Kaloustian and Diab, 2015).

In addition to the rise in urban temperatures, the heat island effect also amplifies the impact that heat waves have on both ecological systems and urban inhabitants in large urban areas (Vermeulen, 2023).

2.6 Heatwaves:

Climate change has led to a rise in the frequency and intensity of weather extremes, with heat waves being a prominent example. Heat waves occur when a region's maximum temperature is at least 5°C higher than the average mean temperature of its hottest month for three consecutive days (Mbokodo et al., 2020). These extreme heat events have adverse impacts on both the environment and socioeconomic aspects worldwide (Mbokodo et al., 2020). South Africa is particularly vulnerable to the effects of such extreme heat (Mbokodo et al., 2020). The increasing global mean temperature is associated with a higher occurrence of heat waves (Mbokodo et al., 2020).

Projections indicate that South Africa will experience a slight rise in heat wave frequency between 2010 and 2039, but a more significant impact is expected during 2070-2099, with an average increase of two heat waves per three-month season per year (Mbokodo et al., 2020). Computer simulations suggest that daily maximum temperatures in the interior of South Africa may increase by up to 6°C during the 2070-2099 period, potentially leading to more intense and frequent heat wave events (Mbokodo et al., 2020).

Heat waves can bring about adverse consequences, encompassing reduced agricultural yields and health issues in human populations. Vulnerable groups such as children and the elderly are particularly at risk, with heat waves potentially leading to elevated mortality rates (Mbokodo et al., 2020). Moreover, water supplies can be impacted as heat waves cause increased evaporation rates. Crops and vegetation can be damaged, resulting in decreased crop production due to the crucial influence of temperature and soil moisture (Mbokodo et al., 2020). To mitigate heat stress, there is often heightened usage of air conditioners during heat waves, which in turn contributes to global climate change (Mbokodo et al., 2020).

The Urban Heat Island (UHI) phenomenon is increasing in prevalence, primarily due to rapid urbanisation and the rising frequency of heatwaves. As a result, urban areas experience an intensifying and unbearable thermal environment during the summer. This leads residents to rely heavily on air conditioners, creating a detrimental cycle that worsens the effects of UHI (Zhou and Chen, 2018).

2.7 Need for adaptation strategies:

By implementing well-planned strategies, cities and buildings can effectively mitigate the UHI phenomenon and improve the urban thermal environment. Urban Heat Island Mitigation Planning is crucial in this regard, which involves incorporating strategies into urban planning and development processes (Zhou and Chen, 2018). Factors such as land use patterns, urban density, and building arrangements should be considered to promote natural ventilation, green spaces, and shading. These measures aid in reducing the heat island effect and enhancing the overall livability of urban areas (Zhou and Chen, 2018).

New cities or buildings offer the opportunity of mitigating the negative effects of the UHI. However, existing cities and buildings will need to adapt in order to address the current and future climate conditions.

It is crucial to acknowledge that the urban landscape of South Africa is primarily composed of built infrastructure and existing buildings, which must endure the developmental strains of global urbanisation, and the adverse impacts of local climate change, such as heat stress on urban residents. While newly constructed buildings can integrate these concerns into their design and development stages, retrofitting will be necessary to enhance the adaptability of existing buildings. This is due to the evolving climate considerations and conditions that differ from those the existing buildings were initially designed to withstand (Vermeulen, 2023).

It is argued that while transition pathways towards climate change adaptation in urban areas are needed, the technical feasibility of architectural technologies for implementation in such transition pathways within South African cities should be considered and developed (Vermeulen, 2023).

2.8 Koppen Geiger Climate Classification:

Understanding the specific climate classification is crucial for studying and proposing effective architectural technologies that can serve as adaptation strategies targeting thermal amelioration potential. Developing a generalised decision framework for thermal adaptation strategies is insufficient, because of the diverse climatic zones that exist globally.

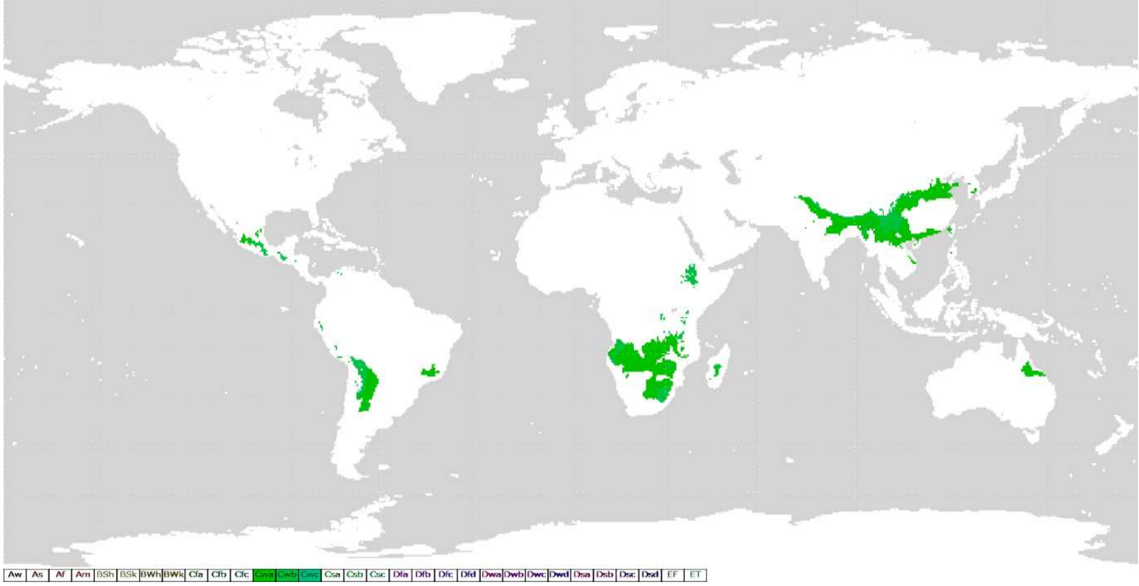


Figure 2 / Koppen Geiger Map, showing all Cwa, Cwb & Cwc regions (Peel, Finlayson and McMahon, 2007)

It is therefore necessary to identify technologies that have been implemented in regions that have the same climatic condition as seen in Tshwane, South Africa.This approach allows for more accurate recommendations to address climate challenges and implement effective adaptation strategies.

The Koppen-Geiger climate classification system was created by Wladimir Koppen in 1900, and remains one of the most widely used climate classification systems today (Peel, Finlayson and McMahon, 2007). It offers a broad framework for regionalizing climate variables and assessing global climate models (Peel, Finlayson and McMahon, 2007). The system divides climates into five main zones (A, B, C, D, and E), with sub-zones based on temperature and precipitation (Peel, Finlayson and McMahon, 2007).

In the City of Tshwane and surrounding areas, various regional climate zones exist, with the most prominent being Cwa, Cwb, and Cwc. These zones are categorised by having dry winters and moderate to hot summers (Peel, Finlayson and McMahon, 2007).

It is essential to acknowledge that while considering built examples that have adopted thermal adaptation strategies, they must correspond to the same climatic zone as Tshwane to be applicable and, therefore, should be situated in these regions.

3. Research Design and Methodology:

3.1 Research Paradigm

Climate change is an urgent matter that requires immediate attention, as substantiated by the available research. South Africa stands particularly vulnerable to the consequences of global warming with escalating heat waves and rapid urbanisation (MacKellar, New and Jack, 2014)(Chersich *et al.*, 2019)(Mbokodo *et al.*, 2020). It becomes imperative for South African cities to prioritise the development of comprehensive strategies aimed at adapting to the challenges posed by climate change in urban settings.

For the strategies to be comprehensive and effective, the implementation thereof must encompass multiple spheres. O'Brien (2018) extensively explored thermal adaptation and identified three interconnected dimensions that require attention. These dimensions include personal, political, and practical aspects.

- The practical sphere, at the core of these dimensions, focuses on the implementation of specific actions, interventions, strategies, and behaviours to attain the desired outcome (O'Brien, 2018). It involves putting in place concrete measures to address climate change impacts.
- The political sphere pertains to the systems and structures that can hinder practical responses. This includes the rules, regulations, and policies established and managed through political processes (O'Brien, 2018). These factors can either facilitate or impede progress in achieving the 1.5°C target.
- Lastly, the personal sphere examines the habits and behaviours of individuals within the built environment. It considers the role of building occupants in adapting to climate change and making sustainable choices (O'Brien, 2018).

The primary objective of this report is to delve into the practical sphere of thermal adaptation. It focuses on implementing physical modifications in buildings to reduce their environmental impact. By addressing this sphere, significant strides can be made towards adapting to the changes in climate and ensuring the long-term sustainability of the built environment.

3.2 Research Paradigm

This review is grounded in a pragmatic paradigm that seeks to address real-world problems and improve the human condition (Breed, 2022). The project adopts a pragmatic approach (Kivunja and Kuyini, 2017), aiming to analyse and comprehend the current potential and response of various climate change adaptation strategies to enhance thermal adaptation in the Tshwane climate. Through this approach the study aims to address the broader issue of climate change within the built environment and proposes implementation strategies to improve the thermal performance of existing buildings.

The pragmatic paradigm allows for a combination of methods to be employed to gain a deeper understanding of the subject matter (Kivunja and Kuyini, 2017). In this study a mixed-method approach is followed, with a relational epistemology focused on sourcing real-life examples of various strategies from grey literature and examining the relationships between them. The ontology of the study can be described as non-singular (Kivunja and Kuyini, 2017), as the grouping of data analysis is subject to individual interpretation. The axiology of the study is value-laden as it is centred around a topic that aims to benefit people (Kivunja and Kuyini, 2017).

3.3 Research Protocol

Torgerson's (2003) five-step framework for developing a protocol will be adapted to guide the data gathering and analysis process in the research report focused on passive ventilation systems. This structured approach provides a systematic and rigorous methodological foundation for conducting a comprehensive analysis of the collected data.

By applying the five steps developed by Torgerson the research aims to ensure the reliability, validity, and transparency of the data analysis process, ultimately contributing to the robustness of the findings and conclusions presented in this study. The following subsections will outline each step of the Torgerson framework as it is adapted and implemented in the context of analysing data pertaining to passive ventilation systems;

Step 1 - Establish research objectives.

Step 2 - Formulate specific research questions.

Step 3 - Formulate method for data collection.

Step 4 - Determine the criteria for including or excluding data in the analysis.

Step 5 - Determine the methods for data analysis.

3.4 Research Objectives

The primary objective of this study is to identify and examine successful strategies that enhance the thermal responsiveness of buildings. Examples collected for this purpose will be investigated from both international and local contexts (Vermeulen, 2022:2).

Various methods will be employed to assess the thermal adaptive capacity of the collected examples. This includes analysing the reported outcomes, efficiencies, benefits, and shortcomings of the building technology. Additionally, technical and material considerations will be thoroughly analysed. This comprehensive analysis will help determine the feasibility of applying these strategies as retrofit options for existing buildings in the Tshwane context. The review will also explore the mutual benefits associated with these strategies, within the broader understanding of their application and effectiveness.

To structure this report effectively, four main objectives have been established:

Objective 01: Identify climate change adaptation strategies.

Objective 02: Compile a comprehensive collection of climate change adaptation strategies.

Objective 03: Analyse the climate change adaptation strategies.

Objective 04: Interpret the data derived from the climate change adaptation strategies.

3.5 Research Questions

3.5.1 Main research Question:

How can / do architectural building technologies implemented in selected case studies, contribute to the local climate adaptation strategies that target thermal amelioration potential?

3.5.2 Sub questions:

SQ 01 What methods are used to assess the thermal adaptive capacity of the building technology?

SQ 02 What are the reported outcomes/ efficiencies/ benefits/ shortcomings of the building technology?

SQ 03 What are the material and technical considerations of the building technology?

3.6 Data collection method: Case studies.

To ascertain the relevance of architectural interventions to the main research question and address sub-questions 1-3, a comprehensive review of diverse literature resources was conducted. While grey literature lacks formal peer-review, it served as a valuable source of information. Employing specific search terms and keywords enabled the identification of various data types, including articles and internet posts. These alternative resources introduced novel and potential alternatives to current thermal adaptation strategies that have yet to be extensively documented by experts and scholars.

3.6.1 Keywords used in data gathering:

Passive Ventilation, Stack Ventilation, Cross Ventilation, Architecture, Temperate Climate

3.6.2 Grey Literature Sources:

Several notable examples of grey literature and unconventional sources include:

- Archdaily.
- Architecture 2030.
- Archidatum.
- Dezeen Magazine.

3.7 Research Limitations, delineation, and assumptions of Data collection:

3.7.1 Koppen Geiger Climate Classification

When writing a research report, two significant limitations need to be taken into consideration. Firstly, it is crucial to recognize that when searching for case studies that have implemented thermal adaptation strategies, it is essential for them to align with the same climatic zone as Tshwane. This ensures that the findings are relevant and applicable to the specific regions under investigation.

The Köppen-Geiger climate classification system identifies the following climate zones applicable to the city of Tshwane: Cwa, Cwb, and Cwc (Peel, 2007).

- Cwa climate is a monsoon-influenced humid subtropical climate known for its temperate conditions, dry winters, and hot summers.
- Similarly, the Cwb climate is described as a subtropical highland climate featuring temperate weather, dry winters, and warm summers.
- Lastly, Peel (2007) characterises the Cwc climate as a cold subtropical highland climate with temperate weather, dry winters, and cold summers.

3.7.2 Dependency on Grey Literature in Data Gathering

Secondly, the research methodology of this study is confined to a desktop study, focusing primarily on the review and analysis of existing case studies. A comprehensive range of resources were consulted to identify relevant case studies for further analysis. These sources include academic literature. Grey literature sources such as : Blogs, presentations, articles and social media were also reviewed for further case study identification.

3.8 Data analysis method.

In the data analysis section of this research report, particular attention is given to the methodological framework employed for conducting the analysis. While the PICO method (population, intervention, comparison, outcome) is commonly referenced in literature reviews , an alternative approach known as the MCO method (mechanisms, context, outcomes) is proposed (Hall et al., 2017). This shift is motivated by the recognition that comprehending the performance of mechanisms requires a deeper understanding of the contextual factors surrounding the intervention (Hall et al., 2017). By adopting and adapting the MCO method, including a new section titled 'Method,' the examination of Identified Case Studies aims to mitigate potential challenges arising from variations in the intervention context. This ensures a more comprehensive and nuanced analysis of the data. The resulting method can then be abbreviated as : CMMO - or Context, Mechanisms, Method and Outcomes.

3.8.1 CMMO Method:

In this research report, the data analysis section utilises the CMMO method as the primary means of analysis. The CMMO method comprises three main themes: Method, Context, Mechanical, and Outcomes. Within each theme, specific subcategories are examined to provide a comprehensive analysis of the collected data.

Context:

- Location: This subcategory delves into the geographical location of the case studies, considering how regional factors might affect the implementation and performance of passive ventilation systems.
- Climate Region: This subcategory explores the specific climate regions in which the case studies are situated, examining the relationship between climate characteristics and the effectiveness of passive ventilation systems.
- Building Typology: This subcategory investigates the various types of buildings included in the case studies, analysing how different building typologies may influence the design and performance of passive ventilation systems.

Mechanisms:

- Strategies: This subcategory focuses on the different strategies employed in passive ventilation systems and their impact on performance.
- Material Considerations: This subcategory explores the role of materials used in passive ventilation systems, examining their influence on effectiveness and efficiency.

- Technical Considerations: This subcategory investigates the technical aspects of passive ventilation systems, such as design parameters, control mechanisms, and operational factors.

Method:

- Methods used to assess the thermal adaptive capacity of the building technology are examined.

Outcomes:

- Recorded achievements.: This subcategory focuses on recorded achievements or realised benefits of each case study.
- Benefits: This subcategory examines the advantages and positive impacts associated with the implementation of passive ventilation systems, considering aspects such as energy efficiency, indoor air quality, and occupant comfort.
- Constraints: This subcategory addresses the challenges and limitations that may arise in the adoption and application of passive ventilation systems, including constraints related to cost, building regulations, and technical feasibility.

4. Literature Review

4.1 Thermal adaptation spheres:

As previously stated, for thermal adaptation strategies to be comprehensive and effective, the implementation thereof must encompass multiple spheres. O'Brien (2018) extensively explored these spheres and identified three interconnected dimensions that require attention. Namely: the personal, political, and practical spheres.

The primary objective of this report is to delve into the practical sphere of thermal adaptation. It focuses on implementing physical modifications in buildings to adapt to current climate conditions. By addressing this sphere, significant strides can be made towards adapting to the current and expected future changes in climate.

4.2 Thermal adaptation & The Built Environment:

Buildings can employ different strategies to either mitigate climate change or adapt to current conditions.

Mitigation strategies encompass a range of measures aimed at mitigating the impact of buildings on climate change by minimising greenhouse gas emissions and energy consumption (Fawzy *et al.*, 2020). These strategies encompass various approaches, including enhancing energy efficiency, incorporating renewable energy sources, implementing sustainable building practices, and adopting environmentally friendly materials and technologies (Fawzy *et al.*, 2020). The primary objective is to effectively reduce the carbon footprint of buildings and mitigate their contribution to global warming (Fawzy *et al.*, 2020).

In contrast, adaptation strategies specifically target the challenges posed by current climatic conditions, such as extreme temperatures, shifting weather patterns, and rising sea levels (UNFCCC, n.d). These strategies can be implemented in two main ways: either integrating them into newly constructed buildings or retrofitting existing structures to enhance their adaptive capacity (UNFCCC, n.d). Illustrative examples of adaptation strategies include:

- Incorporating design technologies that decrease reliance on artificial cooling/heating for thermal comfort (UNFCCC, n.d).
- Implementing flood-resistant measures (UNFCCC, n.d).
- Using resilient construction materials (UNFCCC, n.d).
- And designing flexible spaces that can accommodate changing needs (UNFCCC, n.d).

Effective adaptation endeavours necessitate a comprehensive evaluation of all the aforementioned strategies. Nonetheless, this report specifically concentrates on design technologies implemented in buildings with the aim of diminishing the dependence on artificial heating and cooling systems.

4.3 Six Categories of Thermal Adaptation Strategies:

Numerous practical methods exist to decrease energy usage required by heating and cooling systems and enhance a building's ability to regulate temperature. The 2022

Research Field Studies team identified six categories of climate adaptation strategies (RFS, 2022), namely:

- Thermal mass Systems
- Roof systems
- Window systems
- Façade systems
- Active design systems
- Passive design Systems

4.3.1 Thermal Mass Systems

Thermal mass refers to the ability of a material or structure to absorb, store, and release heat energy. In buildings, it operates by absorbing heat during warmer periods and releasing it during cooler periods, thereby helping to stabilise indoor temperatures and reduce the need for mechanical heating or cooling (Sharaf, 2020).

4.3.2 Roof Systems

Roof systems in buildings refer to the components and design elements of the roof that contribute to thermal adaptation. They can include insulation, reflective coatings, green roofs, and ventilation features. These systems operate by reducing heat transfer, reflecting sunlight, providing insulation, and promoting natural airflow to improve comfort and energy efficiency (EBC, 2020).

4.3.3 Window Systems

Window systems in buildings refer to the design, materials, and features of windows that contribute to thermal adaptation. They can include double or triple glazing, low-emissivity coatings, and insulated frames. These systems operate by reducing heat transfer, preventing air leakage, and controlling solar radiation to enhance comfort and energy efficiency (CIBSE, 2015).

4.3.4 Façade Systems

Facade systems in buildings refer to the external envelope or outer skin of a building that helps to regulate heat transfer and optimise energy usage. These systems can include insulation, shading devices, solar panels, and ventilated facades. They operate by controlling solar radiation, reducing heat gain or loss, and promoting natural ventilation to enhance comfort and energy efficiency (Givoni, 1998).

4.3.5 Active Design Systems

Active design systems utilise mechanical devices such as HVAC systems, fans, and pumps to actively control temperature and airflow within the building. These systems operate by actively supplying heating or cooling as needed, often in conjunction with passive strategies, to maintain comfort and energy efficiency (Chen, Yang and Lu, 2015).

4.3.6 Passive Design Systems

Passive design systems rely on design elements such as insulation, orientation, and natural ventilation to minimise the need for mechanical heating or cooling. They operate by utilising the building's inherent characteristics to regulate temperature and maximise energy efficiency (Chen, Yang and Lu, 2015).

While it is important to acknowledge the significance of all the listed thermal adaptation strategies, and their inherent thermal mitigation potential, this research paper will primarily concentrate on the last system. Namely – Passive Design Systems.

4.4 Passive adaptation strategies:

4.4.1 Introduction of Passive Design

The term "passive" typically denotes inactivity or non-participation. However, when it comes to architectural design, "passive" carries a specific meaning. It refers to a deliberate approach that maximises the utilisation of natural resources and environmental conditions (Passive House Institute, 2021). The aim is to achieve energy efficiency and enhance comfort within built environments. (Passive House Institute, 2021). The Passive House Institute defines passive design as an approach that "…*employs a set of building principles used to attain a quantifiable and rigorous level of energy efficiency within a specific quantifiable comfort level*." (Passive House Institute, 2021).

Passive design is an approach in architectural design and engineering that harnesses natural elements such as sunlight, airflow, and thermal mass. The objective is to create indoor environments that are comfortable and minimise the reliance on mechanical systems (*Passive Building Design - an overview | ScienceDirect Topics*, no date). It emphasises passive measures, including building orientation, insulation, shading, natural ventilation, and efficient use of materials (*Passive Building Design - an overview | ScienceDirect Topics*, no date). Passive design strategies are primarily aimed at achieving thermal comfort and energy efficiency. According to the Passive House Institute, passive design principles aim to create "*comfortable indoor temperatures throughout the year while using very little energy for heating or cooling*" (Passive House Institute, 2021).

In addition to reducing reliance on artificial heating or cooling, incorporating passive strategies into the built environment brings numerous benefits.

4.4.2 Benefits of incorporating Passive Design

4.4.2.1 Energy Efficiency:

Passive design plays a pivotal role in drastically reducing energy consumption in buildings. By employing strategies like proper building orientation, insulation, and natural ventilation, the reliance on mechanical heating, cooling, and lighting systems is minimised, leading to significant energy savings. Research by Chen, Yang, and Lu (2015) suggests that specific passive design principles can potentially reduce building energy consumption required for cooling by as much as 80% during summer months (Chen, Yang and Lu, 2015)..

4.4.2.2 Thermal Comfort:

Passive design strategies create comfortable indoor environments by regulating temperature and minimising temperature fluctuations. Proper insulation, shading devices, ventilation and thermal mass help maintain stable indoor temperatures (Mirrahimi *et al.*, 2016). It is advocated that two-thirds of thermal discomfort could be eliminated by the judicious use of simple passive designs (Chen, Yang and Lu, 2015).

4.4.2.3 Low-Cost Implication:

Integrating passive design principles into a building provides significant cost effectiveness in terms of both initial capital investment and ongoing expenses (related to energy consumption).

The application of passive design strategies, such as precise building orientation, greatly enhances a building's ability to mitigate thermal conditions, all while requiring minimal to no extra costs. This makes it an economically efficient approach for conserving energy (Chen, Yang and Lu, 2015).

By decreasing energy usage, passive design generates substantial savings for both building owners and occupants, resulting in lower energy bills, reduced maintenance costs, and decreased operational expenses (Chen, Yang and Lu, 2015) (Spanos, Simons and Holmes, 2005).

These tangible financial benefits make passive design a compelling choice for sustainable and cost-conscious building projects.

4.4.2.4 Improved Indoor Air Quality:

Passive design advocates for natural ventilation, which allows fresh outdoor air to flow into buildings, effectively enhancing indoor air quality by minimising the buildup of pollutants and regulating moisture levels. According to Awbi (2003), natural ventilation has a positive influence on indoor air quality and contributes to the well-being of occupants (Awbi, 2003).

4.4.2.5 Environmental Sustainability:

Passive design aligns with sustainable practices by minimising energy use and greenhouse gas emissions. It helps reduce a building's environmental footprint and contributes to global efforts to mitigate climate change. The United Nations Environment Programme highlights passive design as a key strategy for achieving sustainable buildings (Liu *et al.*, 2022).

4.4.2.6 Resilience:

Passive design strategies enhance a building's resilience to external factors such as power outages or extreme weather events. Natural cooling and heating strategies ensure that buildings can maintain comfortable conditions even during temporary disruptions in energy supply (Altan *et al.*, 2016).

4.4.2.7 Adaptability and Flexibility:

Passive design principles can be applied to various building types and climates. They offer flexibility for integration into new construction projects or retrofits. Passive design can work in tandem with active systems, providing an adaptable approach to building design (International Energy Agency, 2013).

Despite the numerous benefits associated with the successful integration of passive design principles, their widespread adoption in the built environment remains limited. This lack of implementation can be attributed to a variety of factors. These obstacles encompass limited capital investment, short-sighted perspectives from building owners, inadequate enforcement of building standards and materials, and insufficient awareness. (Bajcinovci and Jerliu, 2016).

4.5 Passive strategies:

As a MProf Design Initiative Treatise (DIT 801) research group, we have identified four main passive design categories.

4.5.1 Passive Ventilation
4.5.2 Daylight
4.5.3 Shading
4.5.4 Thermal Inertia

Each of these four categories operates through distinct mechanisms and encompasses multiple specific passive design strategies.

4.5.1 Passive ventilation

Passive ventilation refers to the use of natural forces, such as wind and buoyancy, to facilitate the exchange of indoor and outdoor air in buildings (Awbi, 2003). It aims to improve indoor air quality and thermal comfort while minimising energy consumption (Awbi, 2003). Key aspects include strategic placement of openings, building orientation, and design features that promote airflow (Awbi, 2003).

Identified Passive Ventilation Strategies (by DIT 801 research group):
- Openable clerestory windows. (Provide convection air current.)
- Elevated roof. (Reduces heat transfer to (insulated) enclosures / envelopes.)
- Fully openable openings. (Enable cross ventilation.)
- Stack ventilation / Solar chimney. (Naturally induce air movement / remove hot air.)
- Louvred intakes / plenum. (Provide a turbulent loop for air circulation.)

Table 1 / Identified Passive Ventilation Strategies (by DIT 801 research group):

4.5.2 Daylight

Passive daylighting refers to the utilisation of natural sunlight to illuminate indoor spaces, reducing the reliance on artificial lighting (Livingston, 2021). Key concepts include optimising window placement, size, and glazing properties to maximise daylight penetration while minimising glare and heat gain (Livingston, 2021). Passive daylighting strategies improve energy efficiency, occupant comfort, and visual quality (Livingston, 2021).

Identified Passive Daylighting Strategies (by DIT 801 research group):
- Roof design directs solar radiation to the southern floor area.
- Roof pitch and elevation consider direct and indirect solar radiation.
- Clerestory windows to promote even distribution of direct / indirect solar radiation.

Table 2 / Identified Passive Daylighting Strategies (by DIT 801 research group):

4.5.3 Shading

Passive shading refers to the use of architectural features and strategies to mitigate solar heat gain and glare in buildings, reducing the need for mechanical cooling and artificial lighting (Maleki, 2011). Key concepts include shading devices, such as overhangs, louvres, and blinds, which block or filter sunlight (Maleki, 2011). Other important aspects include building orientation, window design, and material selection to optimise shading effectiveness. Passive shading strategies enhance thermal comfort, energy efficiency, and visual comfort (Maleki, 2011).

I*dentified Passive Shading Strategies (by DIT 801 research group):*
- PV panels used as window shading devices.
- Planting / Green space in proximity to buildings.
- Shading Screen (PVC, polyester fibre, etc.)

- Screens (Specialist fabrics/materials with translucent and opaque properties) that reflect and absorb sunlight to minimise UV radiation.

Table 3 / Identified Passive Shading Strategies (by DIT 801 research group):

4.5.4 Thermal Inertia

Thermal inertia refers to the ability of materials with high thermal mass to absorb, store, and release heat, thereby stabilising indoor temperatures (Straube and Burnett, 2005). Key concepts include the selection of appropriate materials, such as concrete or stone, and their strategic placement in the building envelope (Straube and Burnett, 2005). Other important aspects include optimising the timing and duration of heat absorption and release to match diurnal temperature variations. Passive thermal inertia enhances energy efficiency and thermal comfort (Straube and Burnett, 2005).

Identified Passive Thermal Inertia Strategies (by DIT 801 research group):
- Draw air from geothermal earth tubes to offset air temperature.
- Limestone used for plinth for mild radiant cooling retention.
- Thermal mass acts as an insulator to regulate interior temperature.
- Phase change materials that are integrated with the façade / roof.

Table 4 / Identified Passive Thermal Inertia Strategies (by DIT 801 research group):

4.6 Passive Heating vs Passive Cooling

Passive design principles encompass a range of strategies aimed at achieving energy efficiency and thermal comfort in buildings (Chen, Yang and Lu, 2015). One way to categorise these principles is by distinguishing between passive design for cooling and passive design for heating.

Passive cooling strategies focus on minimising heat gain, enhancing natural ventilation, and utilising shading techniques to maintain comfortable indoor temperatures in warm climates (Nguyen and Reiter, 2014). On the other hand, passive heating strategies concentrate on maximising solar gain, optimising insulation, and employing thermal mass to retain and utilise heat in colder climates (Nguyen and Reiter, 2014).

According to the research findings, the rising average temperatures and more frequent heat waves in South Africa will heighten the demand for cooling to ensure occupants' thermal comfort (Bugenings and Kamari, 2022) (Mbokodo et al., 2020). However, this increased need for cooling contradicts the current efforts of the EU to achieve climate neutrality.

Therefore, there is a clear necessity for measures to adapt to these climate effects (Bugenings and Kamari, 2022). The increasing reliance on air conditioning for cooling has become a significant cause for concern. The International Energy Agency (IEA) reports that air conditioning and electric fans collectively account for approximately 20% of global electricity consumption in buildings (Archdaily, 2023).

Implementing passive design systems involves considering both heating and cooling requirements. However, It is crucial to acknowledge the statistics that highlight the substantial impact of air conditioning on energy consumption. These statistics underscore the importance of exploring and promoting passive design alternatives for cooling

4.7 Passive cooling strategies:

Prior to the introduction of refrigeration technologies in construction, and the subsequent improvement in thermal comfort, designers employed natural approaches to address climate conditions (El Hadji, 2019). Their aim was to mitigate excessive heat and regulate heat influx from the environment (El Hadji, 2019). These strategies, known as passive cooling methods, were refined and incorporated into building designs over numerous centuries (El Hadji, 2019).

Passive cooling strategies can be, implemented on various scales (Urban Scale, Building Scale or Envelope Scale) divided into three primary categories (Santamouris *et al.*, 2007):

1. Heat Prevention.
2. Heat Modulation.
3. Heat Dissipation.

Heat prevention, heat modulation, and heat dissipation are distinct approaches in managing thermal conditions.

- Heat prevention involves strategies and measures aimed at minimising the entry of heat into a space or building.
- Heat modulation focuses on controlling and regulating the amount of heat within a space or building.
- Heat dissipation involves actively removing or dissipating heat from a space or building.

The passive strategies identified by the DIT research group (refer to Table 1-4) can be categorised into three groups. Each category addresses a specific scale, either urban or building/envelope, and contributes to passive cooling in unique ways.

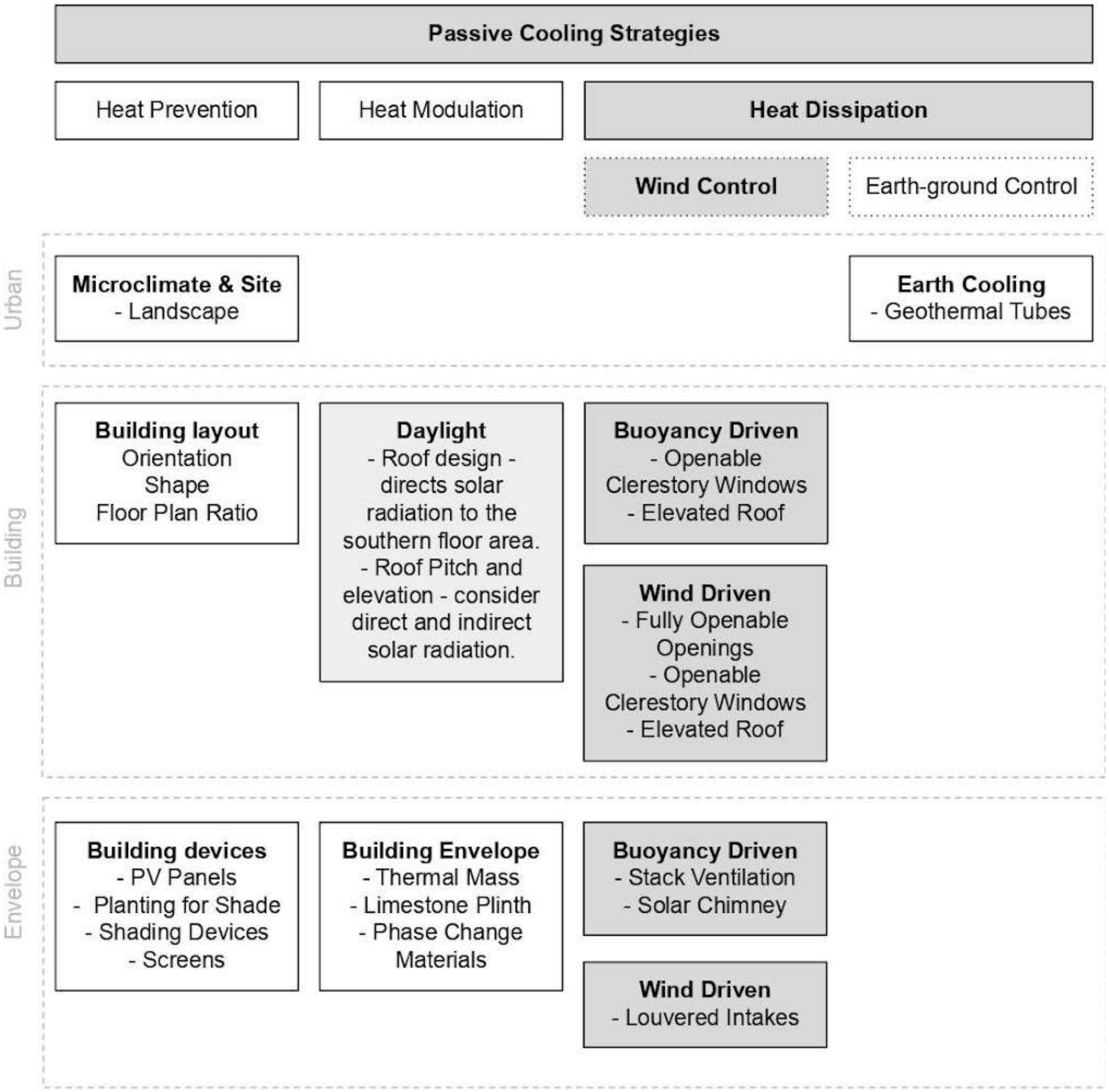


Figure 3 / Identified Passive Cooling Strategies adapted from (El Hadji, 2019) :

This study specifically focuses on passive cooling strategies that facilitate heat dissipation to achieve cooling effects. The investigation will explore wind control measures that utilise both stack and cross ventilation techniques. These ventilation methods aim to effectively dissipate accumulated heat within a building, thereby contributing to the cooling process.

4.8 Passive Ventilation as an effective cooling strategy in Temperate (Cwa, Cwb and Cwc) climate regions:

While the study found limited research regarding the efficacy of passive cooling strategies in temperate climates (Cwa, Cwb, Cwc), certain studies have indicated promising results for passive ventilation as a means of cooling in these regions (Prieto *et al.*, 2018)(Mushtaha *et al.*, 2021). A study conducted by Prieto et al. (2018) explored this topic and highlighted that ventilation strategies exhibited the highest potential for achieving cooling savings in desert, dry temperate, and humid temperate climates (Prieto *et al.*, 2018). Notably the study suggests that the effectiveness of these strategies was found to be heavily reliant on climate conditions rather than the inherent characteristics of the building itself. Built examples in Temperate climates demonstrated superior thermal performance whereas those in highly humid environments experienced less desirable outcomes (Prieto *et al.*, 2018). This is further substantiated in the study by Mushtaha et al. (2021) that identified natural ventilation as a highly effective approach for mitigating extreme heat hazards in temperate climate regions (Mushtaha *et al.*, 2021).

4.9 Passive ventilation strategies:

Passive ventilation efficiently aids in cooling buildings by facilitating the movement of air. (El Hadji, 2019). Natural ventilation not only helps lower the temperature inside the building but also satisfies the requirement for fresh air, while promoting the evaporation of moisture and heat dissipation from the body (El Hadji, 2019). The effectiveness of passive ventilation strategies are influenced by the interplay of two forces: Stack Ventilation and Cross Ventilation.

4.9.1 Stack Ventilation (Buoyancy Driven)

Stack ventilation relies on the temperature difference between the external and internal environments (El Hadji, 2019). This approach operates on the principle of thermal buoyancy, where heated air expands, decreases in density, and ascends. As a consequence the pressure within the indoor space becomes higher at the upper regions and lower at the lower regions (El Hadji, 2019). By strategically placing two openings in the building envelope, one at the bottom and another at the top, a pressure difference is created. This pressure difference causes air to flow inward through the lower opening and outward through the upper opening. (El Hadji, 2019). This phenomenon that is characterised by the entry of cool air through the lower opening and the exit of warm air through the upper opening, is commonly referred to as the stack effect (El Hadji, 2019).

Omrani proposes three categories of natural ventilation strategies for tall buildings (Fig. 4). In Type A, each floor is independent with no connections to vertical voids, relying primarily on wind for ventilation (Omrani et al., 2017).

Type B comprises high-rise buildings with central voids and large internal openings, leading to pressure differential challenges (Omrani et al., 2017). As a single-cell structure, the overall height determines the pressure difference caused by buoyancy forces, resulting in significant pressure drops at lower levels, making it challenging to open windows (Omrani et al., 2017).

To address excessive pressure differentials in buildings with central voids, Type C introduces the concept of Segmentation (Omrani et al., 2017). Each segment is isolated, mimicking a low-rise building, aiming to overcome pressure challenges and optimize natural ventilation (Omrani et al., 2017)..

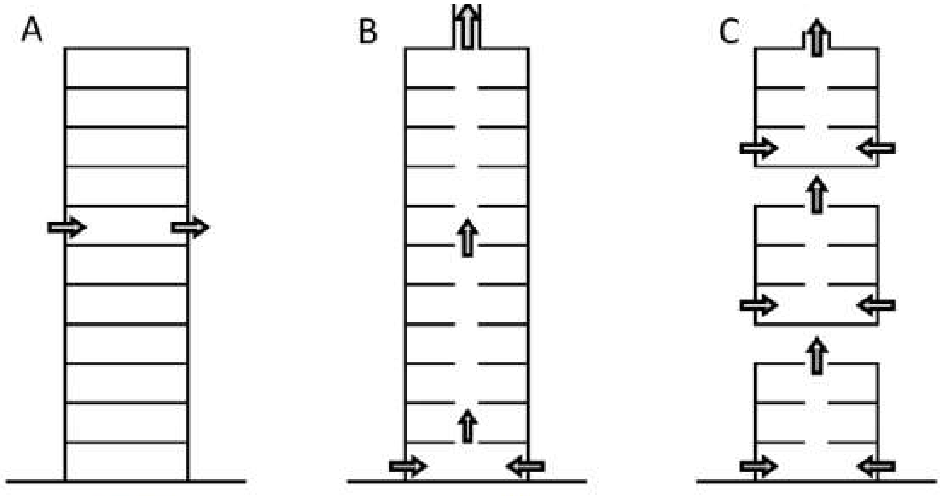


Figure 4 / Ventilation strategies in Tall Buildings. (A - Whole Floor covered) (B - Central void connected floors) (C - Segmentation) (Omrani et al., 2017) :

4.9.2 Cross Ventilation (Wind Driven)

Cross ventilation is a technique that utilises wind flow impacting the building. Wind pressing against a building creates pressure differentials. These pressure differentials establish distinct pressure zones within the building (El Hadji, 2019).

As the wind presses against the building it induces reduced pressure regions on the leeward wall, and above the roof generates a suction zone (El Hadji, 2019). The specific locations on the building envelope where pressure discrepancies emerge guide the placement of openings to enable the phenomenon of cross ventilation (El Hadji, 2019). This process entails air entering through openings characterised by higher pressure and traversing the building to exit through openings situated in the lower pressure zone (El Hadji, 2019).

The adoption of natural ventilation strategies results in decreased energy consumption and improved indoor environmental quality in comparison to buildings relying solely on mechanical systems (El Hadji, 2019). Achieving satisfactory comfort conditions in warm climates through natural ventilation alone is challenging. In such scenarios it becomes imperative to complement natural ventilation techniques with supplementary methods that enhance indoor thermal comfort (El Hadji, 2019). This entails a meticulous integration of the building with the site planning, building mass, and building envelope. Referred to as "*advanced passive cooling,"* this approach strives to optimise the cooling potential while maintaining energy efficiency (El Hadji, 2019).

Passive ventilation can be attained through the utilisation of wind, buoyancy, or a combination of both as driving forces. The efficacy of the selected passive ventilation strategy can be predicted and evaluated through a range of distinct methods. In the subsequent section, a concise overview of some of these methods will be presented.

4.10 Assessing the Effectiveness: Methods for Passive Ventilation Measurement

Omrani proposes various techniques for evaluating the efficiency of passive ventilation. These methods can be classified into three primary groups (Omrani et al., 2017) :

4.8.1 Analytical and empirical methods,

4.8.2 Computational simulation, and

4.8.3 Experimental methods.

Each group can be further subdivided. The suitable approach for assessing natural ventilation may involve choosing one or combining multiple groups from these categories (Omrani et al., 2017).

4.10.1 Analytical and Empirical Methods

Analytical and empirical approaches both utilise fluid flow equations to assess passive ventilation effectiveness, but they differ in their foundations (Omrani et al., 2017). Analytical methods rely on fundamental mathematical fluid dynamics and heat transfer theory, while empirical methods are based on experimental measurements and observations (Omrani et al., 2017).

However, both methods face challenges due to the need for numerous assumptions, simplifications, and approximations to derive closed equations, which can impact result accuracy (Omrani et al., 2017). Additionally, these simplifications may overlook certain higher-order fluid flow parameters, limiting the applicability of these methods (Omrani et al., 2017). Despite these limitations, analytical and empirical correlations remain valuable tools for designers, providing estimations of ventilation performance for simple scenarios, though they may not be as well-suited for complex geometries (Omrani et al., 2017).

4.10.2 Computational Simulation

Computational fluid dynamics (CFD) is a powerful method used to solve the governing Navier-Stokes equations, allowing for precise determination of fluid dynamic properties influencing airflow movement (Omrani et al., 2017). While computationally complex, CFD provides detailed insights into airflow patterns both inside and outside buildings, including air velocity, temperature, pressure, and particle concentration distribution (Omrani et al., 2017). The accuracy of CFD results depends on factors like grid quality, boundary conditions, and model assumptions (Omrani et al., 2017).

Integrating CFD with experimental measurements serves three main objectives (Omrani et al., 2017):

- Visualising and analysing experimental data with different parameters.
- Gaining insights into flow physics not easily obtainable solely through experiments.
- Validating CFD models for subsequent similar studies.

The versatility of CFD allows it to simulate various subjects, design alternatives, and operating conditions, including wind speed and temperature variations, making it a valuable tool for designers in the analysis and design processes (Omrani et al., 2017).

4.10.3 Experimental Methods

Experimental methods employ diverse measurement techniques to assess flow characteristics, encompassing air velocity, temperature, pressure, and humidity (Omrani *et* *al.*, 2017). These measurements can be performed on both small and full-scale models. Small-scale models utilise a reduced scale representation of the building, while full-scale experiments are typically carried out either within the actual building or on a full-scale model within a laboratory setting (Omrani *et al.*, 2017). The experimental methods described by Omrani primarily serve the purpose of validating mathematical or computational techniques, especially CFD (Omrani *et al.*, 2017).

4.11 Gap in research:

Numerous research papers have been conducted on the efficiency and benefits of passive design principles as well as the various methods of measuring the efficacy (El Hadji, 2019)(Santamouris *et al.*, 2007)(Chen, Yang and Lu, 2015)(Mirrahimi *et al.*, 2016)(Omrani *et al.*, 2017). Yet a significant gap in knowledge exists regarding the efficiency of Passive Ventilation (and the methods of analysis) in Temperate climates.

This report aims to add to the discourse surrounding climate change adaptation, particularly focusing on passive ventilation as an effective cooling strategy. The primary objective is to assess the efficiency of passive ventilation systems and evaluate reliable methods for measuring the effects of Passive Ventilation in Temperate climate regions. By doing so, this study aims to bridge the existing knowledge gap and offer valuable insights into the potential benefits and challenges associated with implementing passive ventilation strategies in these regions.

More specifically, the research outcome of this study aims to contribute to the existing research on the retrofitting of multistorey buildings in Tshwane. By examining the efficiency of Passive Ventilation Strategies in Temperate climates, this research aims to provide valuable insights and recommendations for retrofitting existing multistorey buildings in Tshwane which target occupant thermal comfort.

4.12 Contextualising data collection and analysis:

The data gathering and analysis section of the research report will focus on real-world examples of passive ventilation in temperate climate regions. This research will examine the practical application and outcomes of passive ventilation techniques in these regions. By applying the CMMO method (as discussed in chapter 3.8.1), the aim is that the analysis provides valuable insights for the development of sustainable and energy-efficient building practices in Temperate climates.

5. Results:

5.1 Identified Case Studies

In the data collection section of this research report, a total of 12 case studies have been identified that incorporate passive ventilation as an adaptation strategy for cooling indoor temperatures. These case studies exemplify the utilisation of heat dissipation methods to achieve the desired cooling effect. Furthermore, all of the identified examples are situated within temperate climates and conform to the Koppen Geiger Climate Classification categories CWA, CWB, or CWC. To source these ca1se studies, reputable architectural websites and Journals were consulted, chosen for their credibility and expertise in the field.

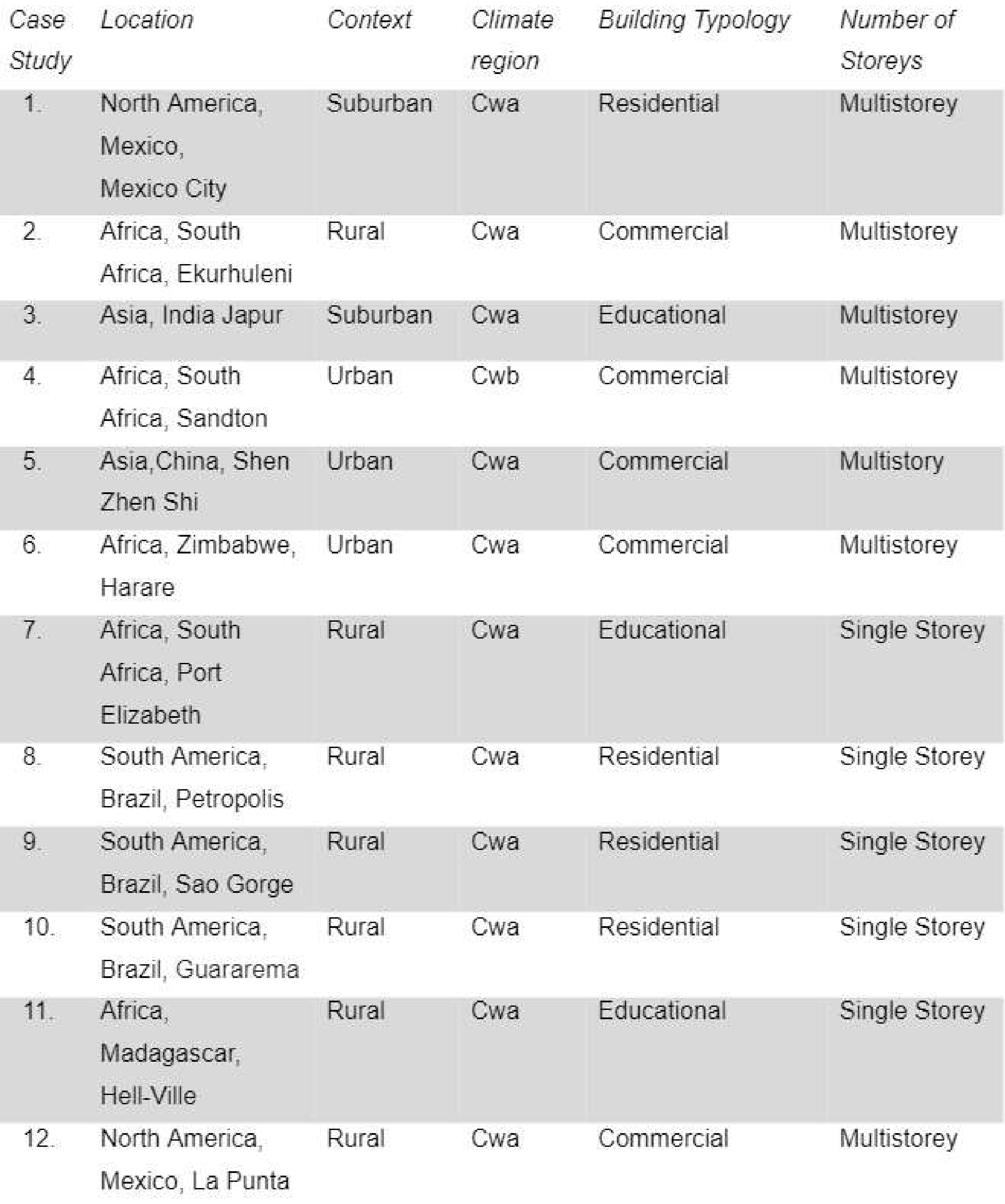
Case Study	Source Type
1. Casa de Vidrio en Chimalistac / Vertical / 2009	Architectural Websites
2. African School for Excellence / Local Studio / 2015	Architectural Website Architectural Journal
3. Pearl Academy of Fashion / Morphogenesis	Architectural Website Architectural Journal
4. Discovery Place / Boogertman & Partners	Architectural Website Architectural Journal
5. Shenzhen Rural Commercial Bank Headquarters / Skidmore, Owings & Merrill	Architectural Website
6. Eastgate Centre / Mick Pearce	Architectural Website
7. Silindokuhle Preschool / Collectif saga	Architectural Website
8. Endless Horizon House / Siqueira + Azul Arquitetura Siqueira + Azul Arquitetura	Architectural Website
9. Palicourea House / BLOCO Arquitetos	Architectural Website
10. Guararema House / Terra e Tuma Arquitetos Associados	Architectural Website
11. Children's Home in Nosy Be / Aut Aut Architettura	Architectural Website
12. House TO / Ludwig Godefroy Architecture	Architectural Website

Table 5 / Identified Case Studies Strategies (by Author)

5.2 CMMO Analysis of the collected Data

5.2.1 Context

During the initial phase of data analysis, a comprehensive contextual analysis is conducted. This analysis entails examining key factors such as the physical location, climate categorization, building typology, and number of stories in the case studies. By considering these aspects, the analysis enables a contextualised understanding of the performance of the case studies.



Case Study	*Location*	*Context*	*Climate region*	*Building Typology*	*Number of Storeys*
1.	North America, Mexico, Mexico City	Suburban	Cwa	Residential	Multistorey
2.	Africa, South Africa, Ekurhuleni	Rural	Cwa	Commercial	Multistorey
3.	Asia, India Japur	Suburban	Cwa	Educational	Multistorey
4.	Africa, South Africa, Sandton	Urban	Cwb	Commercial	Multistorey
5.	Asia,China, Shen Zhen Shi	Urban	Cwa	Commercial	Multistory
6.	Africa, Zimbabwe, Harare	Urban	Cwa	Commercial	Multistorey
7.	Africa, South Africa, Port Elizabeth	Rural	Cwa	Educational	Single Storey
8.	South America, Brazil, Petropolis	Rural	Cwa	Residential	Single Storey
9.	South America, Brazil, Sao Gorge	Rural	Cwa	Residential	Single Storey
10.	South America, Brazil, Guararema	Rural	Cwa	Residential	Single Storey
11.	Africa, Madagascar, Hell-Ville	Rural	Cwa	Educational	Single Storey
12.	North America, Mexico, La Punta	Rural	Cwa	Commercial	Multistorey

Table 6 / Contextual analysis of Case Studies (by Author)

5.2.2 Mechanisms

The 12 case studies are analysed based on the employed mechanisms, including ventilation type (wind-driven or buoyancy-driven) and material considerations for each case. Additionally, each case study analysed according to the passive ventilation strategy present (as listed in Table 1 of chapter 4.4.1). These strategies are highlighted in bold under the "Passive Ventilation Strategy and Technical Considerations" column. Relevant technical considerations from the grey literature are also included.

Case Study	Passive Ventilation Type	Material Considerations	Passive Ventilation Strategy and Technical Considerations
1.	Wind Driven Ventilation	- Plastered Brick and Glass.	**Fully openable openings** - Demolition of several internal walls to increase airflow. - Predominant East West Cross Ventilation
2.	Buoyancy Driven Ventilation	- Steel and Polycarbonate	**Openable Clerestory Windows** - Double Volumes, allowing hot air to rise and escape through openings.
3.	**Segmented** Buoyancy Driven Ventilation	- Local stone, steel, glass, and concrete.	**Stack Ventilation** - Courtyards that act as a chimney for hot air to rise in. - Stepped ground floor that allows for both cross and stack ventilation.

4.	**Central Void** Buoyancy Driven Ventilation	- The building structure is constructed with a reinforced concrete frame, and its facade features a double-glazed aluminum frame curtain wall.	**Stack Ventilation** - HVAC system managed by centralised plants located on the roof and distributed through shafts alongside the central core. Return air moves upwards through the atriums and is drawn back into the plant rooms through a vast ventilation plenum surrounding the atrium void (Pearce, 2016). - The HVAC system incorporates an economy cycle cooling feature, utilizing outside ambient air whenever possible to cool the interior space. This approach leads to substantial energy savings for a significant portion of the year (Pearce, 2016).
5.	**Central Void** Buoyancy Driven Ventilation	-The building structure is constructed with a reinforced concrete frame, and its facade features a double-glazed aluminum frame curtain wall..	**Stack Ventilation** - The tower utilizes automated louvres in its vertical atria, extending throughout its height, and incorporates mechanized window vents on each office floor. This adaptable system allows the building to "breathe" and make the most of the frequent periods of pleasant weather in Shenzhen.
6.	**Central Void** Buoyancy Driven Ventilation	- Brick, reconstructed stone, steel and glass	**Stack ventilation** - Architecture as Biomimicary. Specifically a termitary.(Eastgate, 2016) - The rooftop features 48 brick funnels. These funnels serve as vents for internal stacks, effectively extracting exhaust air from the seven office floors below. (Pearce, 2016)

7.	Wind Driven Ventilation	- Recycled and reclaimed materials.(palettes, corrugated sheets, scrap metal, cardboard)	**Elevated Roofs** - The space between the two layers of roof sheeting permits air circulation, enabling the top layer to cool down during the summer and prevent overheating inside the classrooms. (Guérin *et al.*, 2017) **Fully openable Openings**
8.	Wind Driven Ventilation	- Wooden panels in geometric forms embedded in a linear stone-clad composition. - Glass-covered pergolas with buriti straw.	**Fully openable Openings** - The indoor spaces receive fresh air, as evident from the internal gardens located within each section. Cross ventilation is facilitated by the presence of sliding, pivoting panels, and folding doors (Endless Horizon House, 2021)
9.	Wind Driven Ventilation	- The architectural design features an exposed concrete structure and solid brick walls, serving as the "core," while the roof is constructed using glued laminated wood (Glulam).	**Fully openable Openings** - Sliding window frames, bug screens, and wooden sliding louvres ensure continuous natural airflow and light. **Elevated Roofs** - The implementation of concrete slabs beneath the elevated roof creates an "air mattress" effect between them and the wooden roof, facilitating an open and naturally ventilated space. This innovative design contributes to improved thermal comfort (Palicourea House, 2021).
10.	Wind Driven Ventilation	- Rammed earth construction system	**Fully openable Openings** - The building emulates a rural housing typology, characterised by two enclosed blocks positioned opposite each other, with an empty space in between. This space features openable sliding doors that

			promote cross ventilation (Casa Guararema, 2022).
11.	Buoyancy Driven Ventilation	- Plastered Brick. Elevated corrugated steel roof. Timber Frame.	**Elevated Roofs** - The rooms are shielded from direct solar radiation, and natural cooling is achieved as the air circulates within the buffer zone between the two layers.
12.	Buoyancy Driven Ventilation	- Concrete, steel, clay, and wood.	**Elevated Roofs,** **Fully openable Openings** **Stack Ventilation**

Table 7 / Mechanism analysis of Case Studies (by Author)

5.2.3 Method for measuring Effectiveness

Methods used to assess the thermal adaptive capacity of the building technology are examined. The 12 case studies are analysed based on the methods used to measure the success of the employed passive ventilation strategy. Not all precedents include a specific measurement method, but most do elaborate on positive outcomes in the grey literature. The measurement methods are categorised into three main types, as discussed in chapter 4.8. Analytical and empirical methods, computational methods, and experimental methods.

Case Study	Method
1. Casa de Vidrio in Chimalistac / Vrtical	N/A
2. African School for Excellence / Local Studio	N/A
3. Pearl Academy of Fashion / Morphogenesis	Experimental methods Computational simulation (Morphogenesis, 13 Nov 2009)

4. Discovery Place / Boogertman & Partners	Experimental methods
5. Shenzhen Rural Commercial Bank Headquarters / Skidmore, Owings & Merrill	Experimental methods Computational simulation (Shenzhen, 2022)
6. Eastgate Centre / Mick Pearce	Computational Methods Full Scale Experimental Methods (Eastgate, 2016)
7. Silindokuhle Preschool / Collectif saga	N/A
8. Endless Horizon House / Siqueira + Azul Arquitetura Siqueira + Azul Arquitetura	N/A
9. Palicourea House / BLOCO Arquitetos	N/A
10. Guararema House / Terra e Tuma Arquitetos Associados	N/A
11. Children's Home in Nosy Be / Aut Aut Architettura	N/A
12. House TO / Ludwig Godefroy Architecture	N/A

Table 8 / Method of measuring, analysis of Case Studies (by Author)

5.2.4 Outcomes

Lastly, the case studies are analysed based on their recorded outcomes, which are divided into three distinct categories: recorded achievements, benefits, and constraints. Benefits are further analysed according to evident thermal comfort benefits, energy efficiency, cost implications, and improved air quality. On the other hand, constraints are subdivided into operational constraints and natural constraints that are specific to the type of ventilation employed.

Case Study	Recorded achievements.	Benefits	Constraints
1.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Aids in heat dissipation and unwanted moisture removal *Improved Air Quality* - Fresh Air Reintroduced into internal spaces. *Energy Efficiency* - Lowered requirement for artificial cooling.	*Natural Constraints* - Velocity of wind could disrupt key pressure zones, thus disrupting the effectiveness of cross ventilation *Operational Constraints* - Openings are manually operated.
2.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Aids in heat dissipation and unwanted moisture removal *Improved Air Quality* - Fresh Air Reintroduced into internal spaces. *Energy Efficiency* - Lowered requirement for artificial cooling.	*Operational Constraints* - Openings are manually operated.
3.	- 100% self sufficient in terms of captive power and water supply	*Thermal Comfort* - Hot air rising through courtyards create a pressure difference on ground floor, causing	

	(Morphogenesis, 13 Nov 2009)	cooler air to be drawn in from the exterior *Energy Efficiency* - Lowered requirement for artificial cooling. *Improved Air Quality* - Fresh Air Reintroduced into internal spaces.	
4.	- 5 Star Green Star rating by the Green Building Council South Africa (Leading Architecture & Design, 2017)	*Thermal Comfort* - Hot air rising through courtyards create a pressure difference on ground floor, causing cooler air to be drawn in from the exterior *Energy Efficiency* - Lowered requirement for artificial cooling.	*Operational Constraints* - Partial reliance on HVAC system for ventilation *Natural Constraints* - units at the lower levels experience a significant pressure drop (Omrani et al., 2017)
5.	- Extensive thermal modelling was employed to establish that the building's energy consumption would be 19% lower than the average building of its size. - The tower has achieved LEED Platinum certification and is currently pursuing a China Green Star certification.	*Thermal Comfort* - Hot air rising through the atrium causing the building to “breathe”. - *Energy Efficiency* - Lowered requirement for artificial cooling.	*Operational Constraints* - Partial reliance on HVAC syst *Natural Constraints* - units at the lower levels experience a significant pressure drop (Omrani et al., 2017)

6.	- Eastgate consumes 35% less total energy compared to six other typical buildings in Harare that rely on full HVAC systems.(Eastgate, 2016) - The cost savings compared to implementing a full HVAC system amounted to 10% of the total building cost.(Eastgate, 2016) - Eastgate's energy consumption is less than 50% of what conventionally air-conditioned buildings use. Despite this substantial energy reduction, Eastgate maintains very satisfactory comfort conditions for all but two weeks out of the entire year.(Eastgate, 2016)	*Thermal Comfort* - Hot air rising through atrium create a pressure difference on ground floor, causing cooler air to be drawn in from the exterior *Energy Efficiency* - Lowered requirement for artificial cooling.	*Operational Constraints* - Need for a control mechanism that effectively utilises the benefits offered by the unpredictable fluctuations in outside air temperature.(Eastgate, 2016) *Natural Constraints* - units at the lower levels experience a significant pressure drop (Omrani et al., 2017)
7.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces.	*Operational Constraints* - Openings are manually operated.

		- Aids in heat dissipation and unwanted moisture removal	
8.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces. - Aids in heat dissipation and unwanted moisture removal	*Operational Constraints* - Openings are manually operated. *Natural Constraints* - Velocity of wind could disrupt key pressure zones, thus disrupting the effectiveness of cross ventilation
9.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces. - Aids in heat dissipation and unwanted moisture removal	*Operational Constraints* - Openings are manually operated.
10.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces.	*Operational Constraints* - Openings are manually operated.
11.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces.	*Natural Constraints* - Unwanted wind could possibly impact the effectiveness of the buoyancy driven stack effect.

12.	N/A	*Thermal Comfort* - Lowered temperature of internal spaces. - Fresh Air Reintroduced into internal spaces.	*Natural Constraints* - Unwanted wind could possibly impact the effectiveness of the cross ventilation.

Table 9 / Outcomes analysis of Case Studies (by Author)

6. Discussion:

Despite the lack of specific research on the effectiveness of passive ventilation strategies for cooling in temperate climates, there is a wealth of built examples in these regions. These examples have all successfully employed passive ventilation techniques that display thermal amelioration potential.

The analysis of case studies 1-12 had a specific objective. The aim was to evaluate the effectiveness of passive ventilation as a cooling strategy in Temperate Climate Regions. The analysis was done based on the CMMO method (Hall et al., 2017). Each case study has been thoroughly analysed based on its unique context and employed mechanisms. The methods used to measure the effectiveness of each passive ventilation strategy have been carefully assessed. And finally, the analysis involves examining the outcomes, including recorded achievements, benefits, and constraints.

6.1 Context Discussion:

The identified studies share a common prerequisite of being situated in a temperate climate region, specifically classified as Cwa, Cwb, or Cwc according to the Koppen-Geiger climate region. Aside from this similarity, the case studies exhibit a wide range of contextual diversity. They are found across different continents, with Africa, Asia, and South America being the most prevalent regions. Moreover, the case studies vary in terms of typology and structure height. Encompassing high-rise commercial buildings, three-story educational facilities, and single-story dwelling units.

This diversity in adopted passive ventilation strategies across a wide range of case studies serves as a preliminary indication. It suggests the potential effectiveness and versatility of these strategies as thermal adaptation methods. This applicability is particularly relevant in temperate climate regions. This is substantiated by the research reports that have focused on the potential of passive ventilation as an effective cooling strategy in Temperate Climates (Prieto *et al.*, 2018)(Mushtaha *et al.*, 2021).

6.2 Mechanism Discussion:

The analysis of the employed passive ventilation strategy involved several steps. First, it required defining the type of ventilation utilised by the strategy. Additionally, it involved carefully considering the various material and technical aspects associated with each strategy. These steps were essential in understanding the mechanisms behind each passive ventilation approach.

6.2.1 Passive Ventilation Types

The effectiveness of passive ventilation strategies hinges on the interplay of two forces: Stack Ventilation (Buoyancy Driven) and/or Cross Ventilation (Wind Driven). Each case study employed either wind-driven ventilation (1, 7-12) or buoyancy-driven ventilation (2-6).

Interestingly, buoyancy-driven ventilation appeared to be the preferred choice for high-rise structures, while wind-driven ventilation was more prevalent in single-story buildings. However, there were instances where some case studies utilised both types of ventilation (1). It is necessary to note that when both ventilation types were present in a case study, they still functioned in isolation

6.2.2 Material Considerations for Wind Driven Ventilation

Material considerations do not appear to directly impact the effectiveness of cross ventilation, as evidenced by the wide range of materials used across various case studies (1, 7-12). Cross ventilation occurs due to pressure differentials, which create distinct pressure zones within the building (El Hadji, 2019). Specifically, air enters through openings characterised by higher pressure and then traverses the building to exit through openings located in the lower pressure zone (El Hadji, 2019).

From these findings, it can be inferred that as long as the construction materials allow for the buildup of pressure zones by facilitating wind flow into a building, successful cross ventilation can be achieved.

6.2.3 Material Considerations for Buoyancy Driven Ventilation

In case studies employing buoyancy-driven ventilation (2-6) there is no clear indication that material choice directly impacts the effectiveness of stack ventilation. As discussed in Chapter 4.9.1, stack ventilation relies on the temperature difference between the external and internal environments (El Hadji, 2019). Stack ventilation operates on the principle of thermal buoyancy. Heated air expands, ascends, and decreases in density, resulting in higher pressure at the upper regions and lower pressure at the lower regions within the indoor space (El Hadji, 2019). This pressure difference causes air to flow inward through a lower opening and outward through an upper opening. (El Hadji, 2019).

The role of materials in buoyancy-driven ventilation can be seen in two aspects: their thermal properties and strategic placement within the building envelope (Straube and Burnett, 2005). Materials that aid in heating the surrounding air can potentially enhance the stack effect, similar to what is observed in the passive ventilation strategy of solar chimneys.

However, in the case studies (2-6) that utilise buoyancy-driven ventilation through internal atriums or courtyards, the amount of solar gain may not be sufficient to achieve an effective "solar chimney" effect.

6.2.4 Technical Considerations for Wind Driven Ventilation

The technical considerations identified for successful cross ventilation, based on relevant case studies, can be grouped into three main factors. Firstly, cross ventilation appears to be most effective when the openings are larger in size, allowing for a greater flow of air. Secondly, the strategic placement of openings opposite each other enhances the airflow and promotes efficient air movement within the space. Lastly, the removal of internal walls or barriers between the two openings is crucial. This unobstructed pathway enables a smoother airflow, contributing to the overall success of cross ventilation.

6.2.5 Technical Considerations for Buoyancy Driven Ventilation

The case studies that employ buoyancy-driven ventilation as the primary strategy for passive cooling carefully consider three key technical considerations (2-6). Firstly, they facilitate the stack effect by incorporating an internal void that runs the entire height of the structure. This void can take the form of an atrium (3-6) or a courtyard (2). Secondly, for cases where the stack effect is facilitated by atriums, the hot air is either returned into a complementary HVAC system (4-5) or released through vents (6). When courtyards are used, the hot air is released back outside (3). Thirdly, to sustain the cooling process, the cool air at the bottom of the stack effect is either recycled from the HVAC system or drawn in from the outside.

6.3 Methods for measuring Discussion:

In Chapter 4.10, various techniques to evaluate the efficiency of passive ventilation are discussed. These methods can be broadly classified into three primary groups, as identified by Omrani et al. (2017): analytical and empirical methods, computational simulation, and experimental methods.An interesting observation emerges when comparing case studies employing wind-driven ventilation as a strategy versus those using buoyancy-driven ventilation. Most of the wind-driven ventilation case studies lack evident methods to measure the effectiveness of the ventilation, while buoyancy-driven ventilation studies tend to utilise various measurement techniques. This is shown in the Table below, indicated by the cells that are highlighted

Case Study	Ventilation Type	Analytical and Empirical Methods	Computational Methods	Experimental Methods
1. Casa de Vidrio	Wind			
2. African School for Excellence	Buoyancy			
3. Pearl Academy of Fashion	Buoyancy		Computational	Experimental
4. Discovery Place	Buoyancy			Experimental
5. Shenzhen Rural Commercial Bank	Buoyancy		Computational	Experimental
6. Eastgate	Buoyancy		Computational	Experimental
7. Silindokuhle Preschool	Wind			
8. Endless Horizon House	Wind			
9. Palicourea House	Wind			
10. Guararema House	Wind			
11. Children’s Home in Nosy	Wind			
12. House TO	Wind			

Table 10 / Methods for measuring discussion Case Studies (by Author)

For instance, in case studies (3-6), the impact of stack ventilation was measured using experimental methods. This involved deploying measuring devices throughout the structure after its construction to assess the passive ventilation strategy's influence on indoor temperature relative to the outside temperature. For example, in The Eastgate Centre by Mike Pearce: Ove Arup & Partners, the engineering team installed a data logger to continuously monitor air temperature at five critical locations (Pearce, 2016).

Additionally, case studies (3, 5 & 6) also made use of various computational methods during the design phase of the structure. These computational approaches offer valuable insights and predictions during the planning stage, contributing to the effectiveness and success of the passive ventilation strategies implemented.

An analysis of the methods of measuring yields two valuable conclusions. Firstly, case studies (3-6) that have employed diverse measurement techniques have also recorded official and substantiated outcomes, validating the effectiveness of the utilised stack ventilation strategies. Secondly, the implementation of such measuring methods contributes to a deeper understanding of the ventilation strategy's effectiveness. It allows for critical reflection by the design and engineering teams, enabling valuable lessons to be learned and applied in future projects (Pearce, 2016).

6.4 Outcomes Discussion:

6.4.1 Recorded Outcomes & Benefits

In Chapter 4.4.2, the utilisation of passive design is explored, and seven key benefits of employing passive design strategies are outlined. These are:

- Energy Efficiency (Chen, Yang and Lu, 2015)
- Thermal Comfort (Chen, Yang and Lu, 2015)
- Low-Cost Implication (Chen, Yang and Lu, 2015)
- Improved Indoor Air Quality (Awbi, 2003)
- Environmental Sustainability (Liu *et al.*, 2022)
- Resilience and Adaptability (Altan *et al.*, 2016)
- Flexibility (Bajcinovci and Jerliu, 2016)

The analysis of outcomes for each case study was performed with a focus on assessing the extent to which they addressed and achieved the aforementioned benefits. This evaluation was based on the benefits listed above, and the results are depicted in the Table below, where the cells highlighted indicate the specific benefits addressed by each case study.

Note that no case study specifically mentions the benefit of: “Resilience and adaptability” or “Flexibility”. As such these two possible benefits are excluded from Table11.

Case Study	Energy Efficiency	Thermal Comfort	Low Cost Implications	Improved Air quality	Environ-mental Sustain-ability
1. Casa de Vidrio	🟩	🟩		🟩	

2. African School for Excellence	🟩	🟩		🟩	
3. Pearl Academy of Fashion	🟩	🟩	🟩	🟩	🟩
4. Discovery Place	🟩	🟩	🟩	🟩	🟩
5. Shenzhen Rural Commercial Bank	🟩	🟩	🟩	🟩	🟩
6. Eastgate	🟩	🟩	🟩	🟩	🟩
7. Silindokuhle Preschool	🟩	🟩		🟩	
8. Endless Horizon House	🟩	🟩		🟩	
9. Palicourea House	🟩	🟩		🟩	
10. Guararema House	🟩	🟩		🟩	
11. Children’s Home in Nosy	🟩	🟩		🟩	
12. House TO	🟩	🟩			

Table 11 / Benefits discussion Case Studies (by Author)

6.4.3 Wind Driven Ventilation Constraints

Constraints observed in the analysis of case studies utilising wind-driven ventilation can be categorised primarily into two groups: Natural Constraints and Operational Constraints. Natural constraints are inherently linked to the functioning of cross ventilation, as wind-driven ventilation relies on pressure zones generated by wind pressing against a building. This means that external wind conditions can significantly influence the effectiveness of the ventilation strategy (El Hadji, 2019).

On the other hand, operational constraints pertain to the manual opening of openings required for cross ventilation to occur successfully. While this manual process may pose functional challenges, it also offers an opportunity to address the natural constraints. By adjusting the openings, desired pressure zones can be created across the structure, aligning with the principles of effective wind-driven ventilation.

This careful classification of constraints allows for a more nuanced understanding of the challenges faced in implementing wind-driven ventilation. By acknowledging both natural and operational constraints, researchers and practitioners can develop strategies to optimize the effectiveness of wind-driven ventilation in different contexts and improve the overall performance of passive ventilation systems.

6.4.3 Buoyancy Driven Ventilation Constraints

Case studies that employ Buoyancy-driven strategies partially rely on HVAC systems as a means of effectively cooling indoor temperatures. This reliance on HVAC systems could be considered an operational constraint since the efficiency of the stack effect relies on the support of a cooling system.

In contrast, constraints for buoyancy-driven ventilation are less susceptible to natural factors. While the stack ventilation system is affected by outdoor temperature, it remains unaffected by pressure zones created by wind (El Hadji, 2019). The stack effect operates as a closed system, with indoor air temperature increasing and rising, while cold air is either drawn in from the outside or recycled from the existing HVAC system (El Hadji, 2019).

This distinction in constraints highlights the interplay between passive ventilation strategies and mechanical cooling systems. While buoyancy-driven ventilation benefits from its independence from wind-induced pressure zones, it necessitates a complementary HVAC system for optimal performance.

However in the case of high-rise buildings with central voids and large internal openings there is another natural constraint. In this scenario, the building functions as a single-cell, and the overall height of the structure determines the pressure difference created by buoyancy forces (Omrani et al., 2017). Consequently, units at the lower levels experience a significant pressure drop, leading to the need for considerable force to open the windows, which may not be feasible (Omrani et al., 2017).

The constraints for each case study are presented in the table below. The cells highlighted in red indicate the specific constraints associated with each case study.

Wind Driven Ventilation	Buoyancy Driven Ventilation	Natural Constraints	Operational Constraints
1. Casa de Vidrio		🟥	🟥
	2. African School for Excellence		🟥
	3. Pearl Academy of Fashion		

	4. Discovery Place	🟥	🟥
	5. Shenzhen Rural Commercial Bank	🟥	🟥
	6. Eastgate	🟥	🟥
7. Silindokuhle Preschool			🟥
8. Endless Horizon House		🟥	🟥
9. Palicourea House			🟥
10. Guararema House			🟥
11. Children’s Home in Nosy		🟥	
12. House TO		🟥	

Table 12 / Constraints discussion Case Studies (by Author)

6.4 Methods vs Benefits vs Constraints:

A detailed analysis of the results is conducted, with a specific focus on three key categories. Firstly, the report examines the methods used to measure the effectiveness of passive ventilation systems. Secondly, it considers case studies that highlight more than four benefits, as discussed in Chapter 4.4.2. Lastly, the report lists case studies that exhibit less than two constraints. These findings are presented in the table below, with cells highlighted in green to signify the respective outcomes.

Case Study	Ventilation Type	Methods for Measuring Incorporated	More than 4 benefits listed	Less than 2 constraints	Total
1. Casa de Vidrio	Wind				0
2. African School for Excellence	Buoyancy			🟩	1
3. Pearl Academy of Fashion	Segmented Buoyancy	🟩	🟩	🟩	3
4. Discovery Place	Central Void Buoyancy	🟩	🟩		2

5. Shenzhen Rural Commercial Bank	Central Void Buoyancy	🟩	🟩		2
6. Eastgate	Central Void Buoyancy	🟩	🟩		2
7. Silindokuhle Preschool	Wind			🟩	1
8. Endless Horizon House	Wind				0
9. Palicourea House	Wind			🟩	1
10. Guararema House	Wind			🟩	1
11. Children’s Home in Nosy	Wind			🟩	1
12. House TO	Wind			🟩	1

Table 13 / Methods vs benefits vs Constraints Case Studies (by Author)

The research findings demonstrate a clear trend, highlighting buoyancy-driven case studies as showcasing more promising results with abundant benefits and minimal constraints. Notably, 4 out of 5 of these case studies have incorporated methods for measuring ventilation effectiveness.

Among these, case study 3 emerges as the most promising example, standing out for its approach of segmentation for ventilation. This unique method has proven to be highly effective in optimising passive ventilation strategies, as evidenced in the literature (Omrani et al., 2017).

7. Conclusion:

The analysis of passive ventilation strategies for cooling in temperate climate regions, based on 12 case studies, provides valuable insights into the effectiveness and versatility of such strategies. Despite the lack of specific research on this topic, the wealth of built examples in these regions demonstrates the potential of passive ventilation techniques in achieving thermal comfort. The examination of each case study was conducted with a specific objective, which was to evaluate the effectiveness of passive ventilation as a cooling strategy in temperate climate regions. The analysis was based on the CMMO method, encompassing the unique context, employed mechanisms, measurement methods, and recorded outcomes of each case study.

The case studies exhibited a diverse range of contextual settings, including various continents and building typologies. This diversity indicates the applicability and effectiveness of passive ventilation strategies as thermal adaptation methods in temperate climates. This finding aligns with previous research that highlights the potential of passive ventilation in such regions.

The mechanisms of passive ventilation strategies were carefully examined, including wind-driven and buoyancy-driven ventilation. Material considerations were found to play a less direct role in the effectiveness of cross ventilation, while strategic placement of openings and the removal of internal barriers were crucial for successful wind-driven ventilation. For buoyancy-driven ventilation, the role of materials was observed in heating the surrounding air to enhance the stack effect.

The methods for measuring the effectiveness of passive ventilation varied among case studies. Notably, case studies employing buoyancy-driven ventilation utilised various measurement techniques more frequently than wind-driven ventilation studies. This suggests a deeper understanding and substantiated outcomes for buoyancy-driven ventilation strategies.

The analysis of recorded outcomes focused on seven key benefits of passive design, such as energy efficiency, thermal comfort, and improved indoor air quality. Each case study was evaluated based on how it addressed these benefits. The findings provide valuable insights for future projects aiming to incorporate passive ventilation strategies.

Constraints associated with wind-driven ventilation include natural and operational factors, while buoyancy-driven ventilation is less affected by external natural constraints. However, buoyancy-driven strategies may require the support of HVAC systems for optimal cooling, introducing operational constraints.

In conclusion, the research findings indicate that buoyancy-driven case studies exhibit favourable outcomes with numerous benefits and few constraints in the context of climate adaptation strategies. The integration of ventilation effectiveness measurement methods in these studies adds to their credibility and robustness. Particularly, case study 3 stands out as a highly promising example, employing the innovative approach of segmentation for ventilation, which has shown significant efficacy according to the existing literature (Omrani et al., 2017).

Future research could prioritise investigating the retrofitting potential of the segmentation approach for passive ventilation in buildings located in temperate climate regions. By examining the adaptability and effectiveness of this strategy in retrofitting existing structures, valuable insights can be gained on its practical application and contribution to climate adaptation in temperate regions. Additionally, this research could explore the potential energy savings and environmental benefits that may arise from implementing the segmentation method in retrofit projects, further enhancing the overall understanding of its viability as a sustainable climate adaptation strategy..

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8.3 List of Tables

8.4 List of Figures