



RESEARCH REPORT

Façades as Climate Adaptation Technologies for Urban Areas in Hot and Temperate Regions of South Africa

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DECLARATION OF ORIGINALITY

I declare that the mini-dissertation, Facades as Climate Adaptation Technologies for Urban Areas in Hot and Temperate regions of South Africa, 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 ethic code for researchers and have followed the policy guidelines for responsible research.

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Date: 28 – 06 - 2024.....

Abstract

Climate change is not a novel occurring phenomenon created by mankind. Climate fluctuations (climate change) have occurred both locally and internationally since the planet originated some 4.5 billion years ago (IPCC, 2007). However, extreme weather events have become more frequent since the 1950s, causing significant damage to the built environment (Kristl, Senior & Salaj, 2020). With projections indicating a significant rise in global temperatures by the end of this century, there is an urgent need for new building requirements and usage patterns (O'Brien, 2018; IPCC, 2018). Policymakers increasingly recognize that both mitigation and adaptation measures are essential responses to climate change (UNFCCC, 2006), with a focus on building resilience at all levels to respond to disruptive events (O'Brien & O'Keefe 2013). Therefore, the focus of the report is to identify and analyse effective and appropriate strategies to enhance a buildings thermal responsive and adaptive capacity in the face of climate change. This study explores how building technology, specifically facade technologies, employed as climate adaptation strategies can enhance the thermal amelioration potential of buildings, specifically in the City of Tshwane (South Africa). The study provides targeted recommendations for enhancing the thermal efficiency and resilience of buildings, advocating for retrofitting existing buildings to cope with evolving climate variations (Vermeulen, 2024). The research findings report that case studies that employed adaptative facades yield the most promising results. Additionally, it was observed that within the framework of the research sample, methods for measuring the thermal performance of the façade technology were only executed on adaptative facades, underscoring its value in temperate climates. The aim of the study is to contribute to the climate change adaptation discourse, emphasising the role of façade systems in enhancing a buildings thermal amelioration potential.

Keywords

Climate change, adaptation, climate adaptation technologies, façade technologies, thermal amelioration, adaptive facades, temperate climate regions

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1. Introduction

The evolution of building purposes and typological characteristics throughout history underscores the enduring need for shelter from varying external conditions within any built space. Modern design and technologies, as observed by Kosanović, Folić & Radivojević (2018), have ushered in an era of independence from external factors, fundamentally altering the traditional consideration of climate in design. Daroda (2011) argues that the shift from vernacular to technological responses is a significant human-induced factor contributing to climate change, disrupting the natural environmental equilibrium.

O'Brien (2018) projects that by the end of this century, the average global temperature will have risen by over 4 °C compared to the pre-industrial period. The IPCC(2018) suggest that this increase is owed to the accelerating pace of climate change and the rising volume of anthropogenic emissions released into the atmosphere each year. According to Kristl, Senior and Salaj (2020), even with current mitigation measures, the average global temperature is expected to increase by 3°C above pre-industrial levels, necessitating new building requirements and usage patterns.

Extreme weather events have become more frequent since the 1950s, causing significant damage to the built environment (Kristl, Senior & Salaj, 2020). The variability of climate change impacts requires consideration across various scales, from regional to micro (Kosanović et al., 2018). Policymakers increasingly recognize that both mitigation and adaptation are essential responses to climate change (UNFCCC, 2006), with a focus on building resilience at all levels to respond to disruptive events (O'Brien & O'Keefe 2013).

The study seeks to contribute to the broader climate change adaptation discourse by emphasizing its significance in South African urban areas, specifically the City of Tshwane. The objective is to research and evaluate successful building technologies that improve thermal responsiveness and adaptive capacity of buildings, with a particular emphasis on façade technologies. The study aims to evaluate the compositional, material, spatial, and technological aspects of façade systems implemented as climate change adaptation strategies, targeting climate amelioration within urban contexts with the same climate classification as Tshwane.

Determining Tshwane's climate zone facilitates a comprehensive analysis of façade technologies suitable for regions with similar climate characteristics. This approach ensures that recommendations for adapting the built fabric in Tshwane to climate change are appropriate, precise, and targeted. The study aims to provide valuable insights into climate-

specific solutions that can enhance the thermal efficiency and overall resilience of buildings in Tshwane. Moreover, the study's relevance transcends local boundaries, addressing global urbanization trends and advocating for the appropriate retrofitting of existing buildings worldwide to better cope with evolving climate variations, ensuring the development of resilient and sustainable cities (Vermeulen, 2024).

2. Background

2.1 Climate Change on a Global Scale

Climate change is not a novel occurring phenomenon created by mankind. Climate fluctuations (climate change) have occurred both locally and internationally since the planet originated some 4.5 billion years ago. The IPCC (2007a) recognised the following climatic variations: the Ice Age of 20,000 years ago (glacial maximum), the Little Ice Age that affected Europe in the early Middle Ages, the subsequent mediaeval warm era, and the cooling of the 17th, 18th, and 19th centuries (IPCC, 2007).

The IPCC (2007a) states that underlying denominator which has caused these climatic variations is the concentration of carbon dioxide (CO₂) in the atmosphere. Carbon is an essential element for sustaining life on Earth, serving as the fundamental building block for all living species including plants, animals, and bacteria. The quantity of carbon dioxide in the atmosphere has played a crucial role in stabilising the climate over long periods of time, thanks to the carbon cycle. In natural conditions, the emission of CO₂ is balanced by carbon sinks, which maintains a stable balance with the energy absorbed from the Sun (IPCC, 2007).

Human actions, especially since the Industrial Revolution, have accelerated the rate at which climate change occurs by modifying the atmospheric chemistry through the burning of fossil fuels, posing a major risk to the fragile equilibrium between human progress and the natural environment (Altomonte, 2008).

The impacts of climate change are increasingly evident in global shifts within the water cycle, atmospheric and oceanic warming, and heightened occurrences of extreme weather events (IPCC, 2018; WMO, 2023). However, O'Brien (2018) underscores that these effects will vary significantly across different regions. Specifically, higher latitudes are expected to experience more pronounced impacts compared to tropical regions (UNFCCC, 2006). Furthermore, weather patterns are projected to become more variable, leading to intensified rainfall in some areas, prolonged droughts in others, and simultaneous occurrences of both phenomena across various regions (UNFCCC, 2006).

Extreme weather and climate events are anticipated to have profound implications on the livelihoods of millions worldwide (IPCC, 2018; WMO, 2023). These events can trigger or worsen issues related to water and food security, health, environmental degradation, urban infrastructure, and population displacement (WMO, 2023). According to the UNFCCC (2006), the most vulnerable groups will typically be the poorest, particularly in developing nations like South Africa, where many rely heavily on the natural environment for their livelihoods (UNFCCC, 2006).

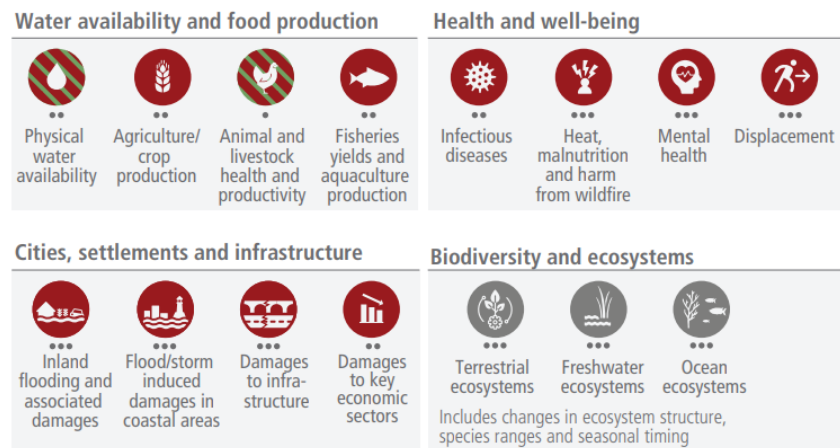


Figure 1: The observed impacts of climate change (IPCC, 2023)

2.2 Global Warming

Human activities have significantly warmed the atmosphere, ocean, and land (IPCC, 2023). The current global warming trend is primarily a result of emissions from decades ago, and the situation is exacerbated by the continuous increase in anthropogenic emissions, particularly carbon dioxide and other greenhouse gases. These emissions create a positive radiative imbalance at the top of the atmosphere, leading to an accumulation of energy within the Earth's system, manifesting as heat. This accumulated heat is the primary driver of global warming (WMO, 2023).

The United Nations Framework Convention on Climate Change (UNFCCC, 2006) asserts that even the most stringent mitigation efforts today will not prevent the inevitable future warming of the Earth's surface. A recent assessment by the Intergovernmental Panel on Climate Change (IPCC) reported that the global temperature has increased by 1.1°C over the past century (1900-2020) and is projected to rise by an additional 1.8 to 4.0°C over the next century, depending on low and high emission scenarios (IPCC, 2023). Furthermore, the IPCC (2018) predicts that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues at the current rate.

Recent global assessments, such as the WMO's State of the Global Climate report of 2023, confirm these trends. According to the report, the average near-surface temperature in 2023 exceeded pre-industrial levels by $1.45 \pm 0.12^\circ\text{C}$, making it the warmest year in recorded history spanning 174 years (WMO, 2023). Moreover, the past nine years (2015-2023) have collectively been the warmest on record (WMO, 2023). This trajectory suggests a steady increase in global temperatures, estimated at approximately 0.2°C per decade (IPCC, 2018). IPCC (2018) projections further indicate that by 2100, atmospheric carbon dioxide concentrations could reach between 540 ppm and 970 ppm, potentially resulting in a global temperature rise ranging from 1.4°C to 5.8°C .

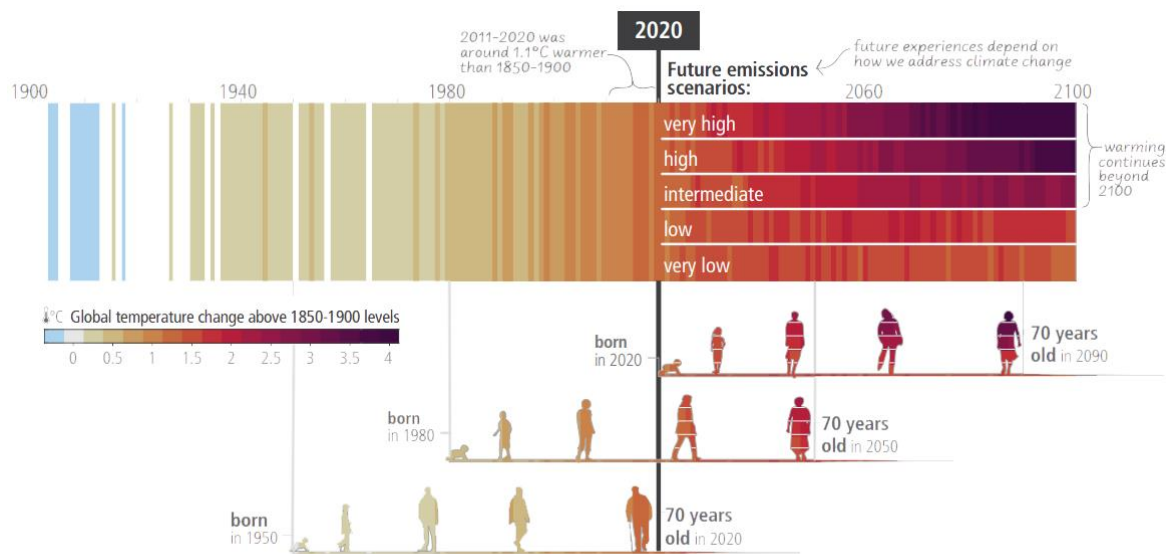


Figure 2: Observed global temperature levels (1900–2020) and projected (2021–2100) changes in global surface temperature and its impacts to the current generation (IPCC, 2023).

The effects of global warming are evident through phenomena such as heat waves, increasing temperatures, and heightened variability in weather patterns, leading to extremes of precipitation and prolonged droughts. These changes are reshaping regional landscapes and conditions (Kosanovic et al., 2018). Understanding the current and future effects of global warming on the built environment is crucial for architects to design spaces that minimize these impacts and safeguard the lives of the inhabitants.

2.3 Urban Heat Island Effect (UHI)

Urban areas significantly alter their local microclimate through the urban heat island (UHI) effect. This phenomenon results from the release of accumulated thermal energy in major urban areas, which raises temperatures beyond their natural levels (Smith, 2009).

The UHI effect was first identified by Luke Howard in London in 1818 and has since been observed in urbanized areas worldwide (Zhou and Chen, 2018). The UHI presents a significant challenge for urban residents and poses an architectural challenge for designers to mitigate and adapt to, as it is more pronounced in urban areas compared to rural ones.

The UHI effect manifests through the building materials and structures in urban areas, which often have high heat capacity and thermal conductivity and are mostly composed of waterproof materials. The building surfaces increase the urban area's underlying surface area, leading to multiple reflections and absorption of heat. These characteristics enhance the amount of heat flux absorbed and stored in urban areas. The presence of numerous tall buildings increases the roughness of urban areas, reducing ventilation and exacerbating heat retention. The unique characteristics and morphology of urban areas lead to increased heat absorption, storage, and convection, resulting in significant heat accumulation. Additionally, anthropogenic heat from human activities further contributes to this accumulated heat (Zhou and Chen, 2018).

With increasing urbanization, the UHI phenomenon is becoming a growing concern, especially in areas with high building density and in megacities (Zhou and Chen, 2018). The effects of UHIs are exacerbated in warmer conditions and seasons, intensifying the urban thermal environment, and making it uncomfortable for residents. This often forces reliance on mechanical solutions like air conditioning, which increases the energy demand of buildings, further contributing to anthropogenic energy creation and emissions (Zhou and Chen, 2018).

Well-planned urban areas can significantly improve their microclimate while minimizing the impacts of climate change on a local scale in the form of the UHI (Lin et al., 2017). Thoughtful urban planning and architectural design are essential in mitigating the UHI effect and creating sustainable, resilient, and liveable cities.

2.4 Greenhouse Gases (GHG)

The increasing concentrations of greenhouse gases (GHGs) in the atmosphere, primarily resulting from human activities such as deforestation, changes in land use, and the burning of fossil fuels, are the major contributors to the climate change phenomenon (Ching, 2014).

The greenhouse effect is a naturally occurring process where gases like carbon dioxide, methane, and nitrous oxide form a canopy over the Earth, trapping some of the solar radiation and thereby warming the Earth's surface (Smith, 2009). Specifically, long-wave radiation emitted by the Earth is reflected back into the atmosphere and then re-radiated by trace gases in the cooler upper atmosphere, causing additional warming (Smith, 2009). This process, known as the greenhouse effect, maintains the Earth's surface and lower atmosphere at an average temperature of 15°C, which is necessary for supporting life (Ching & Shapiro, 2020). Without this natural greenhouse shield, the Earth would be 33°C cooler, rendering it inhospitable for current life forms (Smith, 2009).

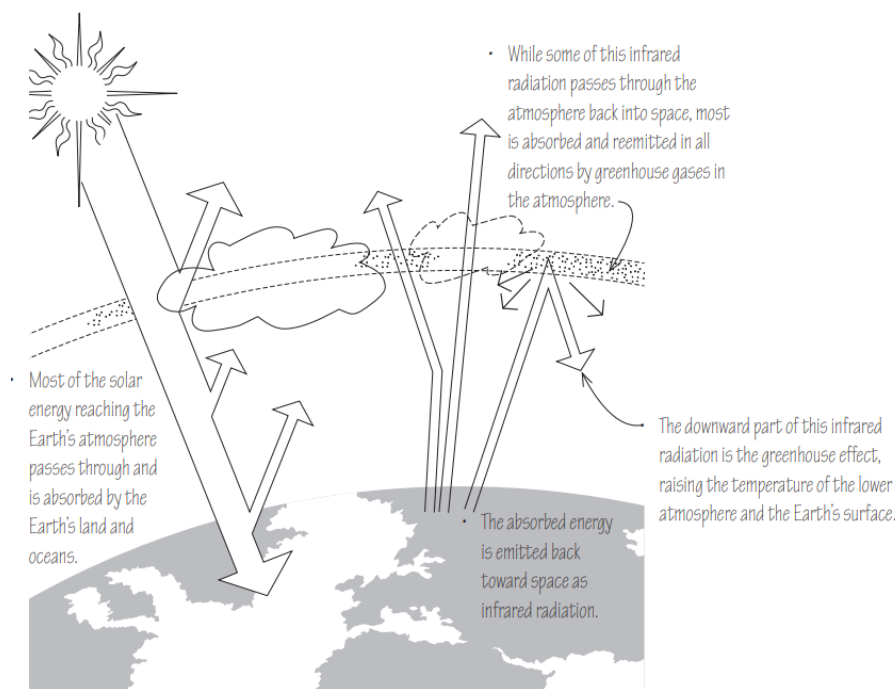


Figure 3: The Greenhouse Gas effect (Ching & Shapiro, 2020)

Since the Industrial Revolution, the excessive burning of fossil fuels has significantly increased the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide, thereby intensifying the natural greenhouse effect and directly contributing to climate change (Ching & Shapiro, 2020). According to the World Meteorological Organization (WMO, 2023), the levels of greenhouse gases have reached unprecedented highs, with globally averaged concentrations of carbon dioxide (CO₂) at 417.9 ± 0.2 parts per million (ppm), methane (CH₄) at $1,923 \pm 2$ parts per billion (ppb), and nitrous oxide (N₂O) at 335.8 ± 0.1 ppb—representing increases of 150%, 264%, and 124% respectively compared to pre-industrial levels (1750).

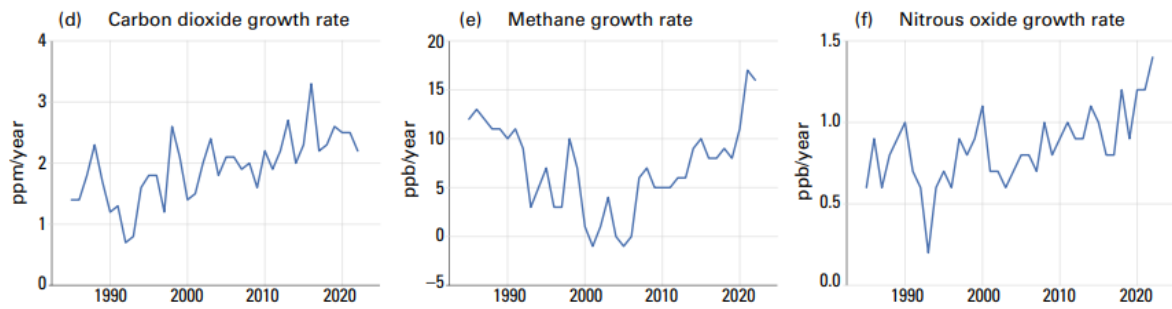


Figure 4: Growth rates representing increases in successive annual means, from 1984 to 2022, of the concentration of greenhouse gases in the atmosphere (WMO, 2023).

These excessive emissions are primarily due to anthropogenic activities. The building industry alone accounts for 26% of global emissions due to the operational energy demands of buildings (IEA, 2023). It is crucial for architects to consider the role of current building practices in mitigating the greenhouse gas phenomenon. This can be achieved by adopting sustainable design principles rooted in traditional architecture (Udyavar, 2006). By properly interpreting location and climate parameters, architects can advocate for climate-responsive architecture—a design philosophy focused on achieving occupant comfort while minimizing reliance on non-renewable energy sources (Yannas, 2003).

2.5 Climate related risks in South Africa

Climate change poses significant risks in South Africa, a country with notably high per capita emissions compared to other nations on the African continent and globally (Ziervogel et al., 2014). South Africa is a substantial emitter of greenhouse gases (GHGs), largely due to the high energy intensity of its economy, which is heavily reliant on mining, minerals processing, and a coal-intensive energy system. This reliance has resulted in an emissions profile that is noticeably different from other developing countries at similar stages of development, as measured by the Human Development Index (RSA, 2011). Given that coal is the most emissions-intensive energy carrier, South Africa's economy is exceptionally emissions-intensive (RSA, 2011).

As a consequence, mean annual temperatures in South Africa have increased by at least 1.5 times the observed global average of 0.65°C over the past five decades, and the frequency of extreme rainfall events has risen (Ziervogel et al., 2014). These trends are projected to continue. The 2013 South African Long Term Adaptation Scenarios and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) predict that warming relative to 1986–2005 will increase between 3°C and 6°C by the period 2081 to 2100 in the interior of South Africa. These increases pose significant threats to South Africa's water resources, food security, health, infrastructure, and its ecosystem services and

biodiversity. Given South Africa's high levels of poverty and inequality, these impacts present critical challenges for national development (Ziervogel et al., 2014).

The specific causes of climate change in South Africa are multifaceted, with electricity generation accounting for around half of the country's energy emissions (RSA, 2011). Effective mitigation and adaptation strategies are essential to address the unique challenges posed by climate change in South Africa, taking into account its economic structure and socio-economic conditions.

2.6 The Built Environment catalysing change

Global warming is already exerting pressure on the built environment, posing challenges to both building energy demand and supply systems (Kristl et al., 2020). The built environment contributes significantly to carbon emissions, accounting for 6.4% and 21% of direct and indirect emissions (Bergamo Dos Santos, 2016). These emissions, comprising of embodied and operational components, impact urban residents' health and well-being. Urbanization and rising electricity demand are key drivers of these emissions, highlighting cities' pivotal role in mitigating climate change by reducing greenhouse gas (GHG) emissions (Bergamo Dos Santos, 2016),

Efforts to reduce building energy consumption and GHG emissions must integrate efficient heating, cooling, ventilation, and lighting strategies (Ching & Shapiro 2020). Urban areas face the dual challenge of adapting to local micro-effects and broader macro-effects driven by the urban heat island (UHI) phenomenon (Smith, 2009).

Despite the urgent need for climate adaptation strategies at the building scale, universally accepted guidelines are currently lacking (Kristl et al., 2020). Progress is underway, however. Efforts to develop sustainable building evaluation standards are ongoing, and the European Union has established a framework of core sustainability indicators (Kristl et al., 2020). Moreover, the European Commission is actively supporting research to advance climate modelling, develop methods and standards, enhance understanding of climate economics, and create technological strategies to improve air quality, reduce city carbon footprints, and establish climate change networks. These initiatives hold promise for establishing clearer guidelines in the future (Kristl et al., 2020).

The built environment must evolve to meet the demands of a changing climate. This involves not only reducing emissions through better design and operation but also adapting to the impacts of climate change to ensure the health and well-being of urban populations. Through

the integration of sustainable practices and technological innovations, cities can play a pivotal role in adapting to climate change, fostering a resilient future.

2.7 Legislative Context

The phenomenon of climate change represents a significant global challenge, prompting numerous countries and international organizations to implement laws and procedures aimed at mitigating its impacts. Given the rapid progression of climate change, conceptualizing it as an adaptive challenge allows for innovative perspectives on both the problems and their potential solutions (O'Brien, 2018). When climate change is viewed through the lens of adaptive challenges, the personal and political dimensions associated with it become critical to the success of technical solutions and strategies (O'Brien, 2018).

This legislative context chapter will explore the political roles that organizations and governments have assumed in addressing the climate change phenomenon. It will also examine the extent of adaptation measures undertaken by various organizations, underscoring the gaps, challenges, and failures of policies. Authorities influence a broad range of stakeholders, from national institutions to local entities, thereby enabling the system to operate based on strategic and regulatory frameworks implemented in the decision-making process (Kristl *et al.*, 2020). By Identifying these legislative and organizational responses, this chapter aims to provide a comprehensive overview of the political dimensions integral to the climate change adaptation discourse.

i. The United Nations Framework Convention on Climate Change (UNFCCC)

The United Nations Framework Convention on Climate Change (UNFCCC) is the principal international institution mandated to address the challenge of climate change. In the 1990s, the Intergovernmental Panel on Climate Change (IPCC) published a series of reports that detailed the extent of greenhouse gas emissions and projected potential consequences through various scenarios. These reports prompted governments to collaboratively draft the UNFCCC, which came into force in 1994 (UNFCCC, 2006).

The ultimate objective of the UNFCCC is to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the natural climate system (Huq and Alam, 2008). This objective underscores the Convention's dual approach of reducing emissions to mitigate climate change impacts and enhancing adaptive capacities to cope with the inevitable changes that are already occurring.

ii. Kyoto Protocol

The Kyoto Protocol, agreed upon in Kyoto, Japan in 1997, represents the first legally binding international agreement that requires developed countries to meet specified emission reduction targets (Huq and Alam, 2008). Under the Kyoto Protocol, most industrialized

nations, with the notable exception of the United States, committed to reducing their carbon dioxide emissions between 2008 and 2012 (Smith, 2009). One of the mechanisms established by the Protocol to achieve these reductions is the capping of emissions from major industrial polluters. Companies are issued permits that allow them to emit a predetermined amount of CO₂ each year, based on their current annual emissions. These permits are tradable under the European Emissions Trading Scheme (ETS), allowing companies that reduce their emissions to sell their surplus permits to those that exceed their emission caps. This market-based approach aims to set a price for carbon, incentivizing reductions in emissions (Smith, 2009).

The Kyoto Protocol's flexibility mechanisms introduce complexity, particularly regarding the provision that allows companies in industrialized countries to invest in emission-reducing projects in developing countries (Smith, 2009). This aspect has been criticized for creating a "grey area" in the system, as it can lead to uneven implementation and verification challenges (Smith, 2009).

The Kyoto Protocol was groundbreaking as the first international legislation aimed at reducing carbon dioxide emissions to mitigate climate change's severe effects. However, its primary shortcoming, as identified by Huq and Alam (2008), was its heavy focus on emission reduction targets without adequately integrating mitigation measures with adaptation strategies to ensure long-term emissions reductions. This limited its effectiveness and highlighted the need for a more balanced approach that combines immediate emission cuts with sustained adaptive responses.

iii. Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The primary objective of the IPCC is to provide governments with scientific information that can inform the development of climate policies, primarily through its Assessment Reports. These reports offer a comprehensive summary of the drivers of climate change, its impacts, future risks, and the ways in which mitigation and adaptation measures can reduce these risks (IPCC, 2024).

The IPCC's Assessment Reports encompass the full scientific, technical, and socio-economic assessment of climate change. Compiled by expert volunteers, these assessments identify the strength of scientific consensus in various areas and highlight where further research is needed within the climate change landscape (IPCC, 2024). By synthesizing the

latest scientific knowledge, the IPCC plays a crucial role in guiding international climate policy and action.

iv. The Paris Agreement

The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 parties at the UN Climate Change Conference in Paris, France, on 12 December 2015 (UNFCCC, n.d.). The primary objective of the Paris Agreement is to limit the global average temperature increase to well below 2°C above pre-industrial levels (1850-1900), with efforts to limit the increase to 1.5°C (UNFCCC, n.d.). This agreement unites all nations in a common cause to combat climate change and adapt to its effects, making it the cornerstone of global efforts to manage climate change effectively (Kristl et al., 2020). By fostering international cooperation, the Paris Agreement aims to strengthen the global response to the threat of climate change and ensure a sustainable future for all.

v. National Climate Change Response White Paper

South Africa's 2011 National Climate Change Response White Paper marks a significant step in outlining the government's responsibilities for both mitigating and adapting to climate change. It emphasizes a sectoral approach while stressing the importance of coordinated responses across different sectors. Despite numerous adaptation options proposed across sectors, there remains a gap in transitioning from managing current climate variability to effectively adapting to future climate change impacts in practical terms (Ziervogel et al., 2014)

The White Paper articulates South Africa's commitment to a climate-resilient and low-carbon economy and society through two primary objectives (RSA, 2011):

- Managing the inevitable impacts of climate change by enhancing the country's social, economic, and environmental resilience, as well as its capacity for emergency response.
- Contributing equitably to global efforts aimed at stabilizing greenhouse gas concentrations in the atmosphere to avoid harmful interference with the climate system. This contribution should occur within a timeframe that supports sustainable economic, social, and environmental development.

These objectives are rooted in constitutional principles, including those outlined in the Bill of Rights, the National Environmental Management Act, the Millennium Declaration, and the United Nations Framework Convention on Climate Change (RSA, 2011). However, specific guidelines focusing on adaptation measures for the built environment are notably absent from the National Climate Change Response White Paper.

2.8 The need for adaptation strategies – Research problem

NASA highlights significant and frequent changes in climate patterns, challenging the conventional 30-year interval definition of climate (NASA, 2005). This dynamic redefines the concept of 'climate design,' moving beyond energy efficiency to essential considerations for long-term building functionality (Kosanović et al., 2018). Kosanovic et al. (2018) advocate for climate change adaptation strategies that enable buildings to adapt continually without frequent upgrades or retrofits. Ferguson, Siddiqi, Lewis & de Weck (2007) define adaptability in the built environment as a system's capacity to maintain intended functionality amid changing conditions by adjusting physical variables over time.

Building Kosanovic *et al.* (2018) insights, David Satterthwaite *et al.* (2009) emphasizes urban centres' dual role in both generating greenhouse gases and developing strategies to mitigate their impact, highlighting the need for reduced reliance on carbon-based fuels. Effective urban planning and management are critical in planning for adaptation, reducing risks to residents, businesses, and infrastructure from climate-related impacts. This adaptive approach extends to buildings, industries, infrastructure, and urban expansion, aligning them with environmental change risks. . Penning-Rowsell (2020) notes the importance in shifting focus in the climate change debate from mitigation to a discussion of combined mitigation and adaptive strategies, which is evident in countries and organisations amending climate change policies to include adaptation strategies.

In South Africa, while there is a recognized need for transition pathways towards climate adaptation in urban areas, there is a crucial gap in understanding the technical feasibility of implementing these architectural technologies within South African cities (Vermeulen, 2023). This research aims to investigate the feasibility and effectiveness of such adaptation strategies in the context of South Africa's urban environment.

2.9 The search for a resilient future

The study focuses on enhancing resilience at the micro scale through adaptation strategies, specifically exploring how building facades can improve thermal performance and adapt to climate challenges. It adopts a bottom-up approach, implementing adaptation measures within buildings to foster resilience at the macro scale within urban contexts.

Resilience within societies refers to their ability to anticipate and plan for changes. Human actions interact with and alter the environment, often transforming it to meet human needs, such as clearing land for agriculture (O'Brien & O'Keefe, 2013). Resilience, therefore, hinges on these human-environment interactions, aiming to enhance both human and environmental resilience. This approach not only mitigates hazards caused by human activities but also prepares for uncontrollable natural events like global warming. Consequently, resilience

becomes a pivotal concept in adaptation strategies, defining a system's ability to absorb and adjust to disruptions or changes.

2.10 Köppen Geiger Climate Classification

The Köppen Geiger Climate Classification System, introduced by Wladimir Köppen in 1900, categorizes the Earth's climates into regions aligned with patterns of vegetation and soils (Koch-Nielsen, 1997). It distinguishes five major climate zones (A, B, C, D, and E), further subdivided based on annual and monthly temperature and precipitation averages (Daroda, 2011). Understanding these classifications is crucial for adapting to climate change impacts, as different regions are affected in varying ways.

To address the research questions effectively, it is essential to analyse regions with climate conditions similar to Tshwane's current and projected climates. This pragmatic approach allows for a comprehensive exploration of how building technologies can adapt to climate challenges in Tshwane and similar regions. In Tshwane, the current climate classification (1980–2016) includes Cwa and Cwb, while future projections (2071–2100) suggest a shift to Bsh.

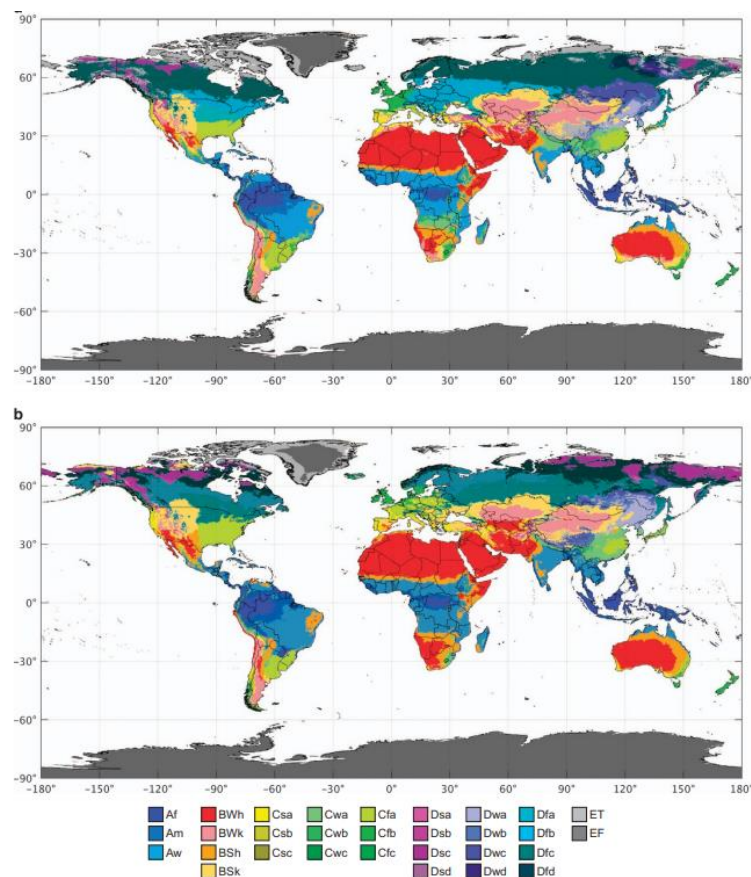


Figure 5: Köppen-Geiger climate classification map at 1-km resolution (Scientific Data, 2018). Map (a) shows the present-day classification (1980–2016) and Map (b) identifies the future climate classification (2071–2100).

(Peel & Finlayson, 2007).

Developing effective adaptation strategies requires consideration of diverse climate zones. The Köppen Geiger system is pivotal in this study for several reasons:

- Regional Comparison: It enables identification of regions similar to Tshwane's climate (Cwa and Cwb), facilitating a comparative analysis of adaptation technologies across similar climatic conditions. This approach assesses the effectiveness of different adaptation strategies in mitigating climate impacts.
- Future Projections: The system provides future climate classifications based on current climate trends. For Tshwane, projections indicate a shift to a Bsh classification by 2071–2100 due to climate change effects. Understanding these future projections helps anticipate and plan for forthcoming climate conditions.

Table 1 outlines the characteristics associated with each classification, guiding the study's focused data collection and analysis efforts.

Table 1: Köppen-Geiger Climate groups with the relative subgroups and associated characteristics (Aksamija, 2013)

Group	Subgroup	Characteristics
B: Dry climate (arid and semi-arid) Lack of precipitation The annual rate of evaporation exceeds the annual rate of precipitation	Bsh : Hot steppe climate	Subtropical dessert Hot semi-arid climate consisting of extremely hot summers and mild winters. The average temperature exceeds 18°C
C: Temperate climate Cw: Temperate climate with dry winters	Cwa : Humid subtropical climates	Precipitation occurs during all the seasons. Humid summers
	Cwb : Temperate climate with dry winters	Dry winters Rainy summers

3. Research Framework and Methodology

3.1 Research Paradigm

This study employs a pragmatic approach to qualitative research, utilizing a meta study research method to conduct an in-depth inquiry into the topic of climate adaptation in the built environment within a real-life setting (Yin, 2018 in Saunders et al., 2019:196). This approach not only allows for the examination of the phenomenon within its real-life setting but also facilitates an understanding of the complex dynamics with which it intersects and from which the case itself is inseparable (Groat & Wang 2013). The dual aims are to address the broader issue of climate change within the built environment and to determine the current and long-term thermal adaptation response of building technologies, implemented both locally and globally, to enhance the thermal adaptation of buildings in the City of Tshwane.

A qualitative research method was employed for data collection and analysis. This method is structured around a systematic literature review and entail investigating grey literature including journal articles and research papers. The study adopts a relational epistemology, focusing on sourcing real-life examples locally and globally, and analysing and comparing the relationships between them. The ontology of the study is described as non-singular (Kivunja and Kuyini, 2017), as the analysis of the case studies is subject to individual interpretation. The primary aim of the study is to contribute to the discourse on climate adaptation technology to address the issue of climate change and its effects within the built environment, thereby improving the lives of the people these structures house. Consequently, the axiology of the study is identified as value-laden (Kivunja and Kuyini, 2017).

3.2 Research Design

The qualitative research design employed in this study adopts a thematic approach to address the research questions comprehensively. This methodological framework is structured as follows:

- Research Methodology: Describes the approach and methods used to collect and analyse data. This section includes details on data sources, data collection techniques, and data analysis procedures.
- Theoretical Framework: Provides the theoretical underpinnings guiding the study, discussing relevant concepts, theories, or models informing the research.
- Findings: Presents the results obtained from the data analysis, includes thematic findings derived from the qualitative data.
- Discussion: Interprets and contextualizes the findings within the theoretical framework, discussing implications, limitations, and connections to existing literature.
- Conclusion: Summarizes the key findings and their significance and highlights contributions to the field and suggests avenues for future research.

3.3 Research questions

3.3.1 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?

3.3.2 Sub-questions

- What methods are used to assess the thermal adaptative capacity of the building technology?
- What are the reported outcomes/ efficiencies/ benefits/ shortcomings of the building technology?
- What are the material and technical considerations of the building technology?

3.4 Research objectives.

The primary objective of the study is to answer the research question through the analysis of data collected from real-life case studies. This will deduce the effectiveness of façade technologies in ameliorating the thermal capacity of buildings in temperate climate regions.

The primary objective of the study is to address the research question by analysing data collected from real-life case studies. This analysis aims to determine the effectiveness of façade technologies in enhancing the thermal capacity of buildings in temperate climate regions. To achieve this, the study has established the following objectives:

1. Understand climate change on both local and global scales.
2. Investigate climate change adaptation technologies.
3. Explore façade technologies employed as climate adaptation strategies.
4. Compile a list of case studies located in temperate and hot climate regions, forming the primary data set.
5. Examine how the façade technologies in the selected case studies improve the thermal amelioration potential of building envelopes.
6. Investigate the methods used to measure the thermal adaptive capacity of façade technologies employed in the case studies.
7. Investigate the material and technical considerations of the façade technologies.
8. Analyse the data to deduce the outcomes of the façade technologies specific to each case study.

By systematically addressing these objectives, the study aims to provide a comprehensive understanding of how façade technologies contribute to local climate adaptation strategies, focusing on their potential to enhance thermal performance in buildings.

3.5 Data collection method: Meta study.

The research methodology begins with a systematic literature review, serving as the foundational taxonomy for the study. The theoretical framework established the scope, direction, and significance of the study and data collection by systematically analysing current research pertinent to the research questions. This involves a comprehensive process of searching, appraising, synthesizing, and summarizing information. The goal is to ascertain a holistic understanding of the current climate change adaptation strategies within the field of architecture and the built environment.

Following the theoretical framework, a qualitative approach to data collection was employed, focusing on the thermal amelioration potential and key terms identified in DIT 801, RFS 701, and the literature review. Data was meticulously recorded and catalogued according to the CMMO analysis framework, ensuring robust exploration of evidence and insights. The data collection from grey literature was executed in 3 phases:

- Phase 1 involved a detailed desktop review of the thermal adaptive building technologies identified in the 2022 UP honours RFS 701 studio.
- Phase 2 entailed the selection of one of the adaptive building technologies identified by the 2022 RFS studio. A desktop study was executed using the key terms identified by the 2022 RFS 701 studio as taxonomy. This phase identified and selected 12 case studies globally and locally, matched with Tshwane's Köppen-Geiger climate classification (Cwb, Cwa, Bsh).
- Phase 3 catalogued published data according to the CMMO analysis framework, focusing on compositional, material, spatial, and technological aspects. This phase specifically examined the benefits, constraints, considerations, and shortcomings of façade technologies implemented as climate adaptive strategies for building envelopes in hot and temperate climate regions.

3.6 Data analysis

Key terms and concepts identified in the 2022 UP honours RFS 701 studio and the theoretical framework establish the analytical framework and taxonomy for analysing selected building technologies employed as climate change adaptation strategies in each case study. The objective of the data analysis is to explore the compositional, material, spatial, and technological aspects, as well as their associated benefits, constraints, considerations, and shortcomings within the studied building technologies.

The study utilizes the CMMO (Context, Mechanisms, Method, and Outcomes) analysis framework, adapted from Jonker's (2023) master's thesis at the University of Pretoria. This framework, derived from the MCO method (Mechanisms, Context, and Outcomes) by Hall et al. (2017), provides a systematic approach to data analysis. Jonker (2023) emphasizes that this adaptation of the MCO method ensures a rigorous examination of the methods used to assess the effectiveness and performance of adaptive technologies, thereby optimizing results and comprehensively addressing the research questions.

The type of data analysed under each subcategory of the CMMO analysis framework is:

- Context: This subcategory identifies the contextual setting of the case studies, identifying factors that influence the façade technology and includes the following information: the building name, architect's name, location, year completed, climate classification, building typology and number of storeys.
- Mechanisms: This subcategory investigates the make-up and assembly of the façade technology by identifying the façade system, type, strategy and material considerations.

- Method: This subcategory identifies the methods employed in each case study that measured the effectiveness or performance of the façade technology.
- Outcomes: This subcategory investigates the performance of the façade system by identifying the recorded achievements (if published), benefits and constraints/limitations of the façade technology. The façade technology's benefits are further categorised into the performance indicators/measures identified in the theoretical framework.

3.7 Limitations, delineation, and assumptions of the study.

3.7.1 Koppen Geiger Climate Classification

The Koppen Geiger climate classification serves as the defining parameter for the scope and context of this study, specifically focusing on regions classified under Cwb, Cwa, and Bsh climates. This restriction ensures the relevance and applicability of the study's findings to Tshwane.

3.7.2 Grey Literature – Desktop studies for Data collection

The qualitative data collection method for the study is limited to a desktop study, which involves reviewing and analysing existing real-life case studies. A diverse array of resources was consulted to identify pertinent case studies for detailed examination. These sources encompass academic literature and grey literature sources. Specific sources utilized in this desktop study include:

- ArchDaily – an architectural website known for its comprehensive coverage of contemporary architectural projects.
- Architect Magazine – a prominent architectural publication offering insights into design trends, practices, and case studies.
- Science Direct – a reputable database providing access to a wide range of scientific and technical research articles.
- Research Gate – an online platform where researchers share and access scholarly papers and publications.

These sources collectively contribute to a robust collection of case studies that form the basis for the qualitative analysis of building technologies as climate change adaptation strategies in the study.

4. Theoretical Framework

The theoretical framework underpins this study by providing a comprehensive set of concepts and theories essential for analysing the data collected on the thermal amelioration potential of facade systems implemented as climate adaptive technologies. Academic literature was consulted in order to answer the research questions. The theoretical framework will delineate the scope, direction, and significance of the study. It will facilitate a systematic approach to understanding climate adaptation technologies and then specifically,

the impact of adaptive facade systems on building thermal performance, guiding the data collection process and analysis. By grounding the study in established theories related to building envelopes, passive design principles, and adaptive technologies, the theoretical framework ensures coherence and depth, enabling a thorough examination of how facade contribute to the broader climate adaptation technology discourse.

4.1 Adaptation Strategies in the Built Environment

Species that adapt to environmental changes thrive, while those that cannot adapt perish (Wigginton & Harris, 2002). Kosanovic *et al.* (2018) asserts that adaptation to the built environment is homogenous with natural organisms. Living organisms exhibit adaptive responses to changing climatic conditions through structural features, like a bird's bill, or behavioural actions for survival (Kosanovic *et al.*, 2018).

Designers face the challenge of integrating sustainable technologies with current building practices to mitigate long-term climate impacts and adapt to immediate changes (Altomonte, 2008; IPCC, 2018). Altomonte (2008) emphasizes that a building's overall design—its structure, envelope, interiors, and services—shapes indoor and outdoor conditions, necessitating integrated design approaches that align with environmental dynamics.

Adaptation strategies in the built environment address current and future climate challenges, such as shifting weather patterns and rising sea levels (UNFCCC, n.d.). These strategies yield multiple benefits, including improved health, enhanced social cohesion, and economic advantages, linking urban and rural areas while fostering sustainable development (IPCC, 2021; Kristl *et al.*, 2020).

Architecture, according to Hawken *et al.* (1999, as cited in Altomonte, 2008), not only shields against natural elements but also fulfils essential functional roles for its users, underscoring the need for buildings to integrate seamlessly with environmental forces. The adaptive responses of living organisms to changing climatic conditions directly correlate with the two types of adaptations in the built environment proposed by Altomonte (2008):

i. Physical adaptation

Physical adaptation involves altering a building's envelope to adapt to climate change. The IPCC (2007) identified that integrated design plays a crucial role in physical adaptations, utilizing both passive and active techniques to provide user comfort and reduce energy requirements. Factors such as thermal performance, ventilation, light distribution, and visual comfort must be balanced and integrated into building design according to specific environmental contexts, climate scenarios, and technical choices (Altomonte, 2008).

vi. Behavioural adaptation

The interaction between building occupants and building systems is likely to change with climate conditions, making the human factor a significant design concern (Kosanovic *et al.*, 2018). Designers should account for the occupants' responsibility and capability to adapt. Behavioural adaptation focuses on the role of building occupants in the adaptation process. Education and training programs can help overcome non-technological barriers to the acceptance and implementation of adaptive strategies and measures, both in households and workplaces. These programs can influence culture, habits, and technology choices, significantly increasing the responsive capacities of buildings and reducing CO₂ emissions (Altomonte, 2008).

Effective adaptation strategies necessitate a comprehensive evaluation of the types of adaptations in order to identify the individual stakeholders' contributions and responsibilities to the adaptation process to create sustainable, comfortable, and resilient built environments that respond effectively to the challenges of climate change. The study will specifically focus on the adaptative technologies of building envelopes with the objective of improving the thermal performance of building envelopes aiming to reduce the dependence on artificial heating, cooling, and light systems.

4.2 The Building Envelope

Behavioural adaptation is an important element to consider when dealing with thermal comfort, however Altan *et al.* (2016) outlines that the building envelope is the physical barrier between natural climate and virtual climate to meet the human comfort level. The nature of behavioural adaptation being a psychological aspect that designers cannot predict but only control through the physical morphology of the building and operational capacity of its parts. This study will deal with the physical adaptation of the building envelope and its components as design strategies to improve the thermal performance of the building, creating comfortable interior conditions.

The building envelope is at the junction of multiple functions to be performed, multiple factors to which it is exposed and numerous stakeholders in the building process (Loonen *et al.* 2015). The building envelope has a great effect on the creation of thermally efficient building design through the implementation of precautionary measures – the fabric of the building envelope, the building morphology and orientation (Yaman, 2021). It must ensure the stability and mechanical strength, health and safety of occupants through the materials composing it, contribute to a proper level of acoustic, visual and thermal comfort and ensure a regulation of transfer (Loonen *et al.*, 2015).

Building envelope design is critical in defining the service demand for heating and cooling, and to guarantee interior comfort and indoor environmental quality (IEA, 2023). Physical adaptations to the building's envelope must consider two factors: energy efficiency and thermal comfort. These two factors are attributed to the heat loss and gain by the façade (Yaman, 2021), relaying the importance of the façade in building design to improve the thermal performance of the building envelope.

4.3 Passive Design Strategies

Buildings present a primary challenge in mitigating climate change due to their substantial energy consumption throughout their life cycle—from construction to operation and eventual dismantling. Building operations account for 30% of global energy consumption and contribute 26% of global energy-related emissions (IEA, 2023). Addressing the energy consumption and emissions of the building sector is crucial to achieve 'Net-Zero Emissions' by 2050 (IEA, 2023). Thus, current buildings must adapt to climate change while simultaneously reducing its operational energy consumption and emissions, which can be accomplished through passive design strategies.

When designing passively, it is crucial to consider several design elements to prevent or minimize heat gain while maximizing user comfort. Key considerations include building orientation, choice of materials, and landscaping (Altan et al., 2016).

Passive design strategies emphasize maximizing the use of natural resources and environmental conditions to minimize reliance on mechanical systems (heating, cooling and lighting systems) for building operations (Passive House Institute, 2021). The primary goal of passive design is to achieve energy efficiency while maintaining or enhancing user comfort within the built environment (Daroda, 2011). Therefore, passive design intricately links the relationship between climate and user comfort.

4.4 Five categories of thermal adaptation technologies to a building envelope

There are several thermal adaption technologies available to improve the thermal performance of building envelopes. The 2022 Research Field Studies team identified five key types of climate adaptation methods (RFS, 2022):

1. Thermal Mass technologies: Thermal mass is a measure of a material/structure's capacity to store, and release heat energy (Sharaf, 2020), improving the thermal adaptive capacity of a building envelope.
2. Roof technologies: Roof system technologies in buildings include a variety of components that increase its thermal adaptability. Insulation, reflective coatings, green roofs, and ventilation features are thermal adaptation measures that roof technologies can employ to increase thermal performance. Therefore, roof

technologies increase comfort and energy efficiency by reducing heat transfer, reflecting sunlight, providing insulation, and promoting natural circulation (EBC, 2020).

3. Window technologies: Window technologies in buildings improve thermal adaptation capacity by including specialised materials and components such as double or triple glass, low-emissivity coatings, and insulated frames. These materials/components limit thermal transmission, air leaks, and sun radiation, improving thermal comfort and energy efficiency of the building envelope (CIBSE, 2015).
4. Facade technologies: Building facades, constantly exposed to the external environment, play a crucial role in thermal comfort and energy efficiency. Well-designed facades help reduce energy consumption and improve indoor thermal comfort (Zhou, Zhang & Wang 2021).
5. Active and Passive Ventilation technologies:
 - Active Ventilation Systems: Active ventilation systems use mechanical equipment (HVAC systems, fans, and pumps) to regulate indoor temperature and airflow. Thereby, actively providing heating or cooling as required to preserve comfort and energy efficiency (Chen et al., 2015).
 - Passive Ventilation Systems: Passive ventilation systems use insulation, orientation, and natural ventilation to reduce the demand for mechanical heating and cooling. They use the building's physical morphology to control temperature and maximise energy efficiency (Chen et al., 2015).

Façade technologies are pivotal in enhancing a building's thermal performance. Therefore, the theoretical framework of the study centres on investigating the thermal impact and performance of these technologies, aiming to establish their efficacy as thermal adaptation solutions for building envelopes. This involves examining facades as integral components of climate-adaptive strategies, highlighting their potential to significantly improve thermal comfort and efficiency in architectural design.

4.5 The façade as a climate adaptative technology

Aksamija (2013) outlines that facades perform two essential functions: it serves as barriers that separate a building's interior from the external environment, and it creates the building's visual identity. Given the current state of climate change, the role of the facade as a physical barrier influencing interior conditions has become more critical than its aesthetic contributions. Yaman (2021) emphasizes that the primary requirement for facades should focus on enhancing energy performance within the building, ensuring adequate daylight, and providing optimal thermal comfort for occupants. These goals are achieved by actively responding and adapting to external environmental conditions (Aksamija, 2015), through

design strategies that consider the location, orientation, and properties of the facade, as well as the implementation of natural ventilation and solar control systems (Yaman 2021).

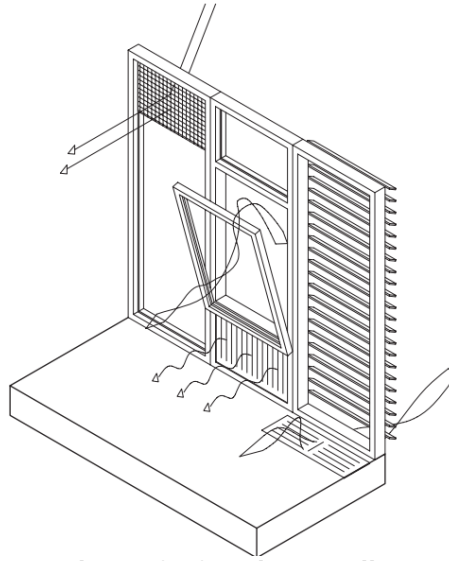


Figure 6: Functions of a facade as a climate adaptive technology (Knaack, Klein, Bilow & Auer 2014)

Different facades perform differently in accordance with their physical behaviours (Aksamija, 2015). These physical behaviours are attributed to the components, materials and construction methods of different façade types generating differing thermal energy loads from the exterior environment through all modes of heat transfer, namely: conduction, convection, absorption, transmission, reflection, and radiation (Knaack, Klein, Bilow & Auer 2014; Sarhan, Gomaa & Zaher 2013).

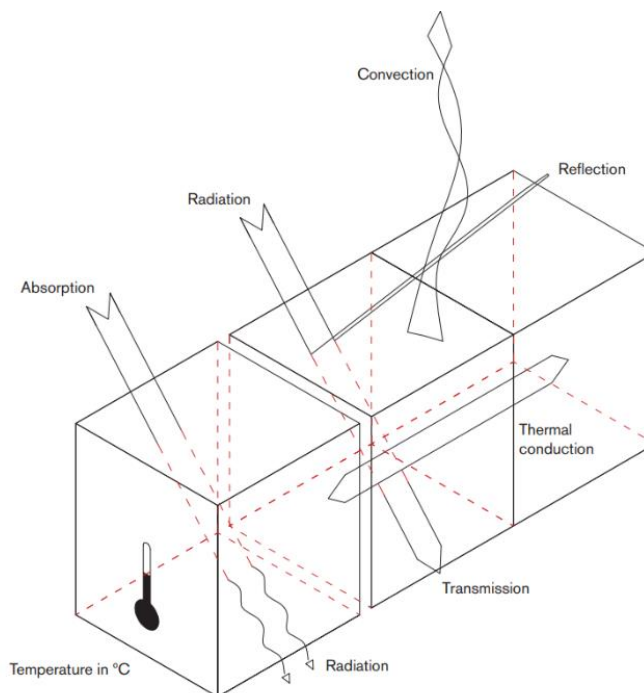


Figure 7: Modes of heat transfer (Knaack et al. 2014)

According to Aksamija (2015), there are essentially only two types of facades:

- Opaque facades: opaque facades primarily consist of layers of solid materials, such as masonry, stone, insulation, precast concrete panels etc.
- Glazed facades: Glazed facades are generally curtain walls, primarily consisting of transparent or translucent glazing materials and metal framing components.

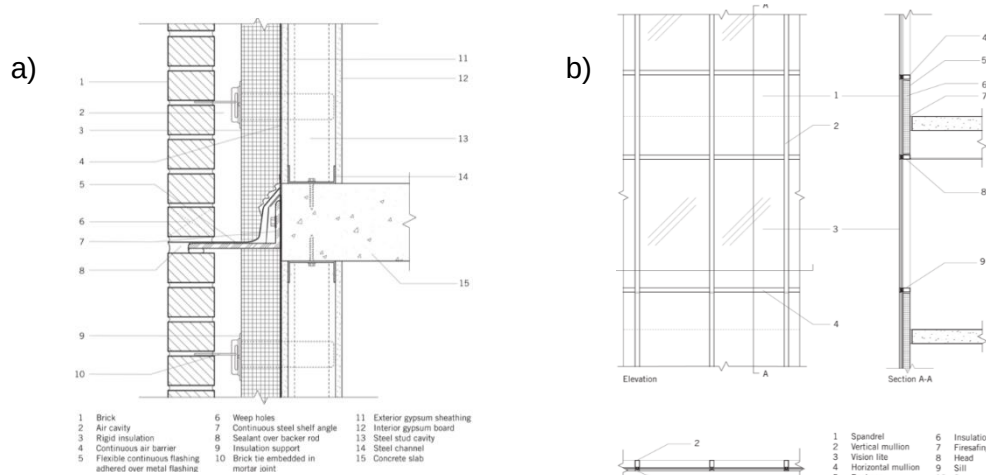


Figure 8: Section through the two types of facades: a) Opaque façade, b) Glazed façade (Aksamija, 2013)

Façades can allow or dissipate air and heat gain through its assemble (Knaack et al. 2014). (Knaack et al. 2014) emphasizes the importance of considering thermal design in façade design. Thermal design is about controlling thermal loads at the building perimeter due to the thermal energy loads from the exterior environment and controlling the internal heat gain loads (Sarhan et al., 2013). Therefore, to understand the importance of facades in thermal design, it is crucial to identify their thermal properties. Aksamija (2013) outlines these properties in the table below:

Table 2: Façade thermal properties identified by Aksamija (2013)

Façade thermal properties	Description
Solar control	The façade can be safeguarded against direct solar radiation using shading devices and self-shading techniques that are integrated into the building's overall morphology (Aksamija, 2013).
Solar collection and passive heating	This involves the compilation of heat from solar radiation through the building envelope (Aksamija, 2013).
Reduction of external heat gains	This entails the protection of the façade from solar heat gain through infiltration or conduction. This can be achieved with well-insulated opaque façade elements and shading devices (Aksamija, 2013).
Heat storage	The ability of opaque façade elements to store heat (thermal massing) (Aksamija, 2013).
Heat conservation	The ability of a façade to preserve the heat within the building. This can be achieved through improving the insulation of the façade elements (Aksamija, 2013).

Daylight	This entails the use of natural daylight while simultaneously reducing solar heat gains. This can be achieved using shading devices and light shelves (Aksamija, 2013).
Cooling	This necessitates the use of passive ventilation by the façade system (Aksamija, 2013) to remove exhaust air from the interior spaces, replacing old air with fresh air.

Considering these thermal properties, contextually, in facade design is crucial for optimizing thermal efficiency and occupant comfort in buildings. Through the integration of facade technologies and strategies, architects can create climate-adaptive buildings that respond dynamically to their environment, reducing the thermal losses of building envelopes while taking advantage of the external environmental conditions as passive design strategies, enhancing overall sustainability.

4.5.1 Thermal properties of façade materials

Aksamija (2015) emphasizes that the meticulous selection of materials is crucial in designing thermally effective facades due to their ability to conduct, resist, store, and radiate heat. The thermal properties of materials significantly impact the thermal performance of facades. The material properties important to consider for façade design are identified in the table below.

Table 3: Material properties important for façade design

Materials thermal properties	Description
Thermal resistance (R-value)	This measures a material's resistance to heat transfer and is expressed in $\text{m}^2\cdot\text{K}/\text{W}$. Measuring the thermal resistance of a façade is the most appropriate way in determining its thermal performance (Aksamija, 2013).
Heat transfer coefficient (U-value)	The U-value, expressed in $\text{W}/\text{m}^2\cdot\text{K}$, represents the rate of heat transmission through a facade assembly's glazed components. It serves as a critical metric for defining the thermal performance of these elements, with a lower U-value indicating better insulation capability (Aksamija, 2013).
Solar heat gain coefficient (SHGC)	The Solar Heat Gain Coefficient (SHGC) quantifies the amount of solar radiation that enters a building through its fenestration. It is represented as a number ranging from 0 to 1, where 0 indicates no solar radiation is admitted, and 1 indicates all solar radiation is allowed to pass through (Aksamija, 2013).
Thermal bridging	Thermal bridging occurs within a facade system when a highly conductive material, such as a metal support, penetrates the facade's insulation layer, thereby lowering the wall's effective thermal resistance (Aksamija, 2015).
Thermal mass	This refers to the ability of a material to absorb, store, and release heat. In well-insulated buildings, thermal mass can significantly reduce heating and cooling loads by minimizing indoor temperature fluctuations (Nadoushani <i>et al.</i> , 2017).

These characteristics underscore the importance of material selection in facade design to achieve optimal thermal performance. By carefully considering these thermal properties, architects can design facades that enhance energy efficiency and occupant comfort.

4.5.2 Façade design strategies influenced by climate.

The building façade serves as the primary interface connecting indoor and outdoor environments. As Yaman (2021) emphasizes, the façade significantly impacts the energy budget and occupant comfort more than any other building system. Achieving satisfactory indoor environmental quality (IEQ) necessitates targeting key factors in façade design: thermal, visual, and acoustic comfort (Soudian & Berardi, 2020). IEQ relies heavily on the balanced exchange of thermal energy, moisture, airflow, sound, and light, all primarily controlled by the façade (Soudian & Berardi, 2020). Table 4 illustrates the impact of various environmental conditions on the IEQ factors identified by Soudian and Berardi (2020) highlighting the importance of façade design in creating thermally comfortable interior spaces for building occupants.

Table 4: The environmental conditions and properties of façade elements which affect IEQ (Aksamija, 2013).

Environmental conditions	Thermal comfort	Visual comfort	Acoustic comfort
Outdoor design criteria	- Sun and wind obstruction - Building dimensions - Air temperature range - Relative humidity range - Wind velocity - Solar radiation	- View and daylight obstruction - Building dimensions - Latitude and locations - Time of day - External horizontal illuminance - Ground reflectivity	- Noise obstruction - Building dimensions - Exterior noise level - Exterior noise source
Indoor design criteria	- Space dimensions - User activity level - Users clothing insulation	- Space dimensions - Colours of surfaces - Working plane location	- Space dimensions - Absorption coefficient of interior surfaces
Indoor comfort criteria	- Air temperature - Relative humidity - Air velocity - Mean radiant temperature	- Illuminance level and distribution - Glare index	- Acceptable interior noise levels

Opaque facades	- Material properties of cladding - Amount of insulation - Effective heat resistance properties (R-value)	- Window-to-wall ratio	- Material selection and properties
Glazed facades	- Orientation - Number of glass layers - Layer thickness - Heat transfer coefficient (U-value) - Visual transmittance - Solar heat gain coefficient (SHGC)	- Orientation - Window properties, size, location, and shape - Glass thickness and colour - Visual transmittance - Reflectance	- Number of layers - Layer thickness - Layer density
Frames and supporting structures for glazed facades	- Thermal properties of the frames		- Material types

When designing thermally effective façades, controlling thermal transmission between external and internal environments is crucial (Aksamija, 2015). The primary factors influencing thermal transmission are the temperature differences between the interior and exterior environments and the façade's ability to resist these thermal energy flows (Sarhan et al., 2013). Different climatic zones necessitate distinct façade strategies for controlling thermal transmission (Aksamija, 2015). This study focuses on two main climate zones: hot (Bsh) and temperate (Cwb & Cwa) climates. Table 3 identifies façade strategies, as discussed in section 4.5 of this study, specifically tailored for hot and temperate climate regions to manage thermal energy flows from the exterior to the interior environment.

Table 5: Façade design strategies for hot and temperate climate regions (Aksamija, 2015)

Climate region	Façade design strategies
Hot climates (Bsh)	- Solar control. - Reduction of external heat gains - Cooling - Daylight
Temperate	- Solar control

climates (Cwa, Cwb)	- Solar collection and passive heating - Daylight
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The objective of façade design in the southern hemisphere, particularly in South Africa, is to respond to its external climate in order to achieve a reduction in thermal losses during winter and minimize thermal gains in summer (Sarhan et al., 2013).

4.5.3 Performance indicators of façades

Attia et al. (2018) established that performance indicators serve as assessment criteria to quantify the success of façade configurations in enhancing thermal conditions both at the building scale and for individual occupants. These indicators gauge the façade's effectiveness in distinguishing between internal and external environments (Kamal, 2020). The relative importance of these indicators influences façade design and the systems implemented. The following performance measures are used to evaluate the thermal performance of a façade system:

i. Thermal comfort

Thermal comfort is defined as the state of mind that reflects satisfaction with the surrounding thermal environment (ASHRAE, 2004). This state encompasses both physiological and psychological comfort (Saini, 1973, as cited in Daroda, 2011). Since building facades are the primary barrier against external conditions, their design significantly impacts the thermal comfort of occupants. Effective façade design requires a thorough understanding and manipulation of external climatic conditions. Aksamija (2013) identifies six key variables for architects to consider in façade design: air temperature, air movement, humidity, mean radiant temperature, occupant's metabolic rate, and clothing.

Thermal comfort, akin to behavioural adaptation, can be viewed as a subjective experience (Aksamija, 2013). Architectural design can influence occupant comfort, highlighting the crucial role of façade design in achieving thermal comfort. Table 6 outlines façade components and their design considerations affecting thermal comfort.

Table 6: Façade components and the relative design considerations for optimal thermal comfort (Aksamija, 2013)

Façade components	Considerations
Windows and glazing	- Surface temperature of glazing in summer and winter months - Daylight and thermal transmittance - Thermal fluctuations caused by windows and glazing - Window-to-wall ratio (WWR) - Thermal characteristics of glazing (U-value and SHG) to optimize thermal performance
Air movement	Undesirable air movement: induced air motion caused by cold interior glazed surfaces and air infiltration from exterior

	environment through gaps in façade
Air infiltration	Air barrier to resist air leakage which is caused by the differing of indoor and outdoor air pressure
Shading elements	Reduces interior solar gains during summer, whilst allowing direct sunlight in winter
Thermal massing	Material selection based on thermal requirements. Insulation Reduction of thermal bridging

ii. Daylight and glare

When designing for daylight and visual comfort, it is essential to consider illumination levels, daylight distribution, and protection against direct sunlight and glare. The primary objective of daylighting systems in façade design is to maximize usable daylight penetration into a building's interior while conserving energy (Aksamija, 2015). Façade strategies for enhancing daylight and reducing thermal gains include:

- Interior sun protection (e.g., interior blinds)
- Shading devices
- Brises-soleil
- Façade planting
- Louvers
- Glass type and vinyl film
- Light shelves

Glare, caused by areas of intense brightness relative to darker areas within the field of view, can cause visual discomfort and impair occupant performance (Aksamija, 2013). Aksamija (2013) suggests the following methods for controlling glare through façade design:

- Window sizing
- Translucent light-diffusing glass
- Glare protection blinds
- Light shelves and light monitors to redirect sunlight.

iii. Acoustic comfort

Façade design plays a crucial role in attenuating unwanted noise from the external environment and enhancing desired sounds within the building envelope (Aksamija, 2013). Acoustic comfort is influenced by sounds transferred from outside and within the building, as well as the occupant's own noise generation (Knaack et al., 2014). The effectiveness of a façade in reducing external noise can be measured by the ambient sound levels inside the building. Passive ventilation strategies may increase indoor noise levels, but these can be predicted and optimized to achieve acceptable acoustic comfort (Aksamija, 2013). If passive strategies fall short, designers can use attenuating elements like acoustic louvers and white noise generators (Aksamija, 2013).

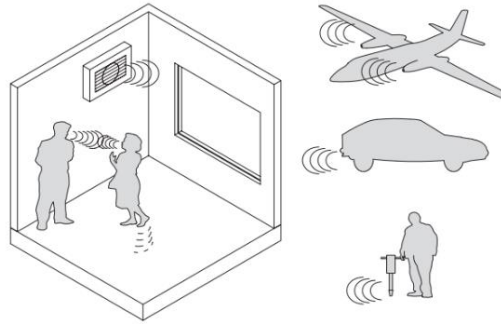


Figure 9: Sources of sound (Knaack et al. 2014)

Aksamija (2013) proposes the following design considerations to enhance the acoustic performance of façades:

- Increase the mass of façade materials to enhance sound transmission loss.
- Match the resonant frequency of façade materials to predominant sound waves for energy absorption.
- Provide acoustic breaks in the façade, like thermal bridging, to hinder sound transmission.
- Use different materials in the façade assembly to create discontinuities and impede sound waves.
- Seal air leaks in the façade to prevent continuous sound wave paths from the external to internal environment.

It can be deduced that the design considerations that improve the facades acoustic performance will ultimately improve its thermal performance (Aksamija, 2013).

iv. Air quality

According to ASHRAE (2007), acceptable indoor air quality (IAQ) means the air has no contaminants at harmful concentrations and satisfies at least 80% of building occupants. IAQ affects occupant health and comfort, making it a key element in creating comfortable interior spaces (Aksamija, 2013). Achieving good IAQ involves exhausting indoor air and introducing fresh air through ventilation methods, which can be passive or active (Table 7).

To reduce air infiltration, Aksamija (2013) recommends sealing air gaps in façades and introducing air barriers.

v. Ventilation

Ventilation impacts user comfort by regulating temperature and humidity, removing odorous and toxic substances, and improving IAQ by replacing exhaust air with fresh air (Knaack et al., 2014). Façades can enhance indoor air ventilation through natural and/or mechanical systems (Knaack et al. 2014).

Table 7: Ventilation systems with their corresponding methods (Knaack et al. 2014).

Ventilation system	Method
Natural ventilation	- Gap ventilation - Window ventilation - Shaft ventilation
Mechanical ventilation	- Extraction through exhaust vents - HVAC - Decentralised ventilation units - aircons

vi. Energy Efficiency

A significant portion of a building's energy consumption occurs during its operation phase (Zhou et al., 2021). As discussed earlier, building operation accounts for 6.4% and 21% of direct and indirect carbon emissions (Dos Santos, 2016), directly contributing to the very cause of climate change. Therefore, buildings must adopt energy-efficient strategies to reduce their climate impact.

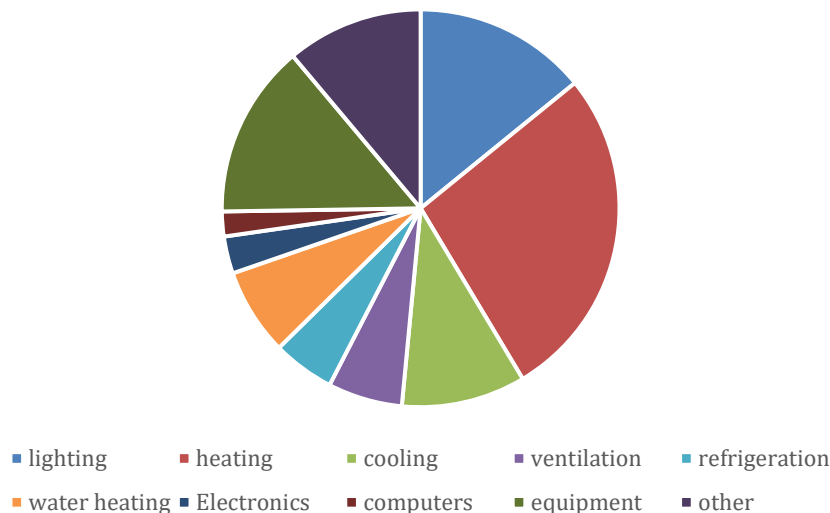


Figure 10: Typical energy use breakdown for commercial buildings (Aksamija, 2013)

Energy-efficient façades employ both active and passive methods to manage solar heat and air infiltration (Aksamija, 2013), thereby reducing the building's energy consumption. Strategies include maximizing daylight penetration, using passive ventilation, minimizing solar glare, preventing heat and acoustic transfer through insulation, and passively managing cooling and heating loads via natural ventilation and thermal mass (Aksamija, 2013). These methods reduce reliance on mechanical systems for building operations.

4.5.4 Façade systems

When considering the performance parameters of façade design strategies, various systems are developed to meet different thermal requirements (Yaman, 2021). Façade systems can

operate either in a passive, active or hybrid manner, depending on external climatic conditions, investment opportunities and façade design strategies.

i. Passive façade systems

Passive façade systems are designed to enhance indoor thermal comfort by mitigating radiant energy through passive design measures. These measures improve the façade's heat-insulating capabilities without relying on artificial energy sources (Zhou et al., 2021). Yaman (2021) describes passive façade systems as self-operating external skins that reduce a building's energy consumption throughout its lifespan. By utilizing natural resources, passive façade systems adopt design principles that optimize thermal comfort year-round by preventing overheating in summer and minimizing thermal losses in winter.

Architects can consider the following design elements when developing passive façade systems:

- Orientation: Positioning the building façade to maximize or minimize direct solar radiation based on the sun's path (Yaman, 2021).
- Shading Elements: Implementing and designing shading devices to control natural light and manage cooling and heating loads from solar radiation (Yaman, 2021).
- Natural Ventilation: Leveraging pressure differences and wind to remove indoor exhaust air, thereby improving indoor air quality and reducing cooling loads (Yaman, 2021).
- Material Selection: Using insulation to control heat and moisture movement and taking advantage of thermal mass to reduce cooling and heating loads (Aksamija, 2015; Zhou et al. 2021)

ii.Active façade systems

Active façade systems include operable mechanical subsystems that make façade elements mobile in response to changing climatic conditions (Yaman, 2021). These systems can support passive systems under varying climate conditions, acting as adaptive and kinetic façade elements that continuously optimize interior thermal comfort (Yaman, 2021). Active systems can be operated manually by building occupants or automatically through integrated management systems.

According to (Kang, Ahn, Park & Schuetze 2015), the following active systems are commonly integrated into façade assemblies to improve the facades thermal performance:

- Self-extinguishing lights
- Controlled ventilation systems
- Operable shading devices
- Photovoltaic elements

Yaman (2021) notes that while active systems often require a higher initial investment compared to passive systems, the evaluation of design versus cost analysis and future investment is essential.

4.5.5 Façade types

As a Mprof Design Initiative Treatise (DIT 801) research group, the following types of façade configurations have been identified:

- iii. Double-skin façades
- iv. Adaptive/Dynamic façades
- v. Green façades

Each of these façade types contains systems discussed in section 4.5.4, integrated with distinct mechanisms, materials, and technologies, rendering different configurations resulting in different performance outcomes and encompassing different strategies.

i. Double-skin facades

A double-skin façade consists of an external glass surface, a shading system, an air-filled cavity, and an insulating double internal glazing, occasionally integrated with opaque surfaces (Asdrubali & Baldinelli, 2007).

The air cavity performs two functions: it creates a thermal buffer between the internal and external environments (Aksamija, 2013) and is used to collect or remove heat from the structure through air flux driven by the buoyancy effect (natural convection) or mechanical devices (Qurraie & Bakırhan, 2023). The buoyancy effect, a passive design strategy, takes advantage of the temperature difference between the external and internal environments, allowing hot air to rise along the cavity and be removed from the façade while fresh air is drawn in through gaps at the lower parts of the façade (Qurraie & Bakırhan, 2023).

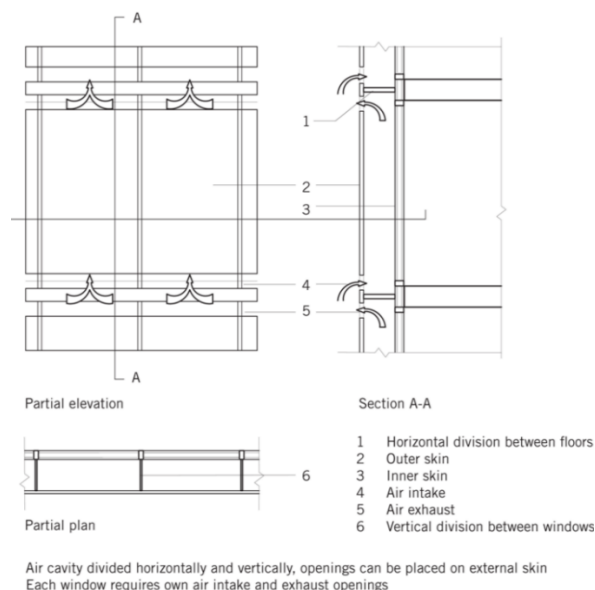


Figure 11: Typical double-skin facade (Aksamija, 2013)

The design of double-skin façades—which includes the selection of glazing type, the width and partitioning of the air cavity, and the ventilation mode—depends on the climate region and building orientation (Aksamija, 2013). The advantages and disadvantages of implementing double-skin façades are listed in Table 8 below.

Table 8: Advantages and disadvantages of double-skin facades (Solmaz 2021)

Feature	Advantages	Disadvantages
Double skin layer	Thermal comfort	Overheating due to inadequate ventilation
Passive ventilation	Clean indoor air quality	Risk of the rapid spread of fire
Sound insulation	Acoustic comfort	Acoustic problems due to inadequate/ failure of insulation
Solar shading	Protection of solar shading elements	Reduction in daylight utilization in case of design failure

ii. Adaptive/Dynamic Facades

In section 4.1 of the study, it is identified that Kosanovic *et al.* (2018) recognised that there are similarities between the adaptative capacity to changing climatic conditions of living organisms and of buildings. These similarities, according to Aksamija (2013), are based on the premise that buildings mimic the adaptative capacity of living organisms as inspiration to effectively adapt building facades to climate change. This is achieved by continuously responding to exterior and interior acoustical, lighting, and environmental conditions. This continuous response is manifested in the design and operation of adaptative façades.

Adaptive façades (AF) are the external skins of building envelopes that can adapt to changing boundary conditions by introducing transient characteristics in the façade design (Soudian & Berardi, 2020). According to Attia *et al.* (2018), the term "adaptive" refers to the capacity of a system or organism to respond to or benefit from outside environmental conditions. Thus, AFs can regulate energy and mass flow through reversible changes in their properties, achieved through advanced technologies and components such as movable shading devices, electrochromic glazing, photovoltaic panels, and phase change materials (Attia *et al.* 2018).

Shafaghat and Keyvanfar (2022) note that adaptive façades are designed based on micro-scale or macro-scale human behaviour and system-driven changes. Therefore, using external conditions to enhance indoor conditions is considered the most appropriate solution. This involves the constant regulation and control of external factors such as heat, ventilation, wind, vapor flow, precipitation, daylight, and noise (Loonen *et al.* 2015). AFs can adapt to these climate factors on a time horizon ranging from minutes to seasonal variations through

the integration of manual or automatic-digital systems (Yaman, 2021). The advantages and disadvantages of adaptive façades are further identified in Table 9.

Table 9: Advantages and disadvantages of adaptive facades (Jamilu, Abdou & Asif 2024)

Feature	Advantages	Disadvantages
Adaptability and flexibility	Constantly adapting to external climate conditions	Noise generation
Environmental footprint	Achieved by actively controlling heat transfer and energy flow, reducing UHI in urban areas	Lack of adequate evidence due to limited long term data on life-cycle costs and performance
Energy generation potential	Integration of energy generation systems into the façade design: integration of photovoltaic components into shading systems	Operational challenges: Response times differ depending on the type of AF
Energy efficiency	Minimize reliance on mechanical systems through the optimization of solar gain, ventilation and daylight.	High-operational energy
Occupant comfort	The creation of thermal comfort through the ability to automatically regulate daylight, temperature and views to achieve optimal user comfort.	Design rigidity: through the limitation of user control options
Solar control	Thermal comfort is created through the mitigation of solar glare and the management of solar radiation	Maintenance requirements with complex AF designs, impacting long-term viability

Attia, Lioure & Declaude (2020) deduced that the aim of Afs is to improve the energy performance and thermal comfort of the building due to fluctuating outdoor conditions, indoor conditions and user requirements.

iii. Green facades

The integration of vegetation on buildings through vertical greening, such as green façades and living walls, significantly improves the building's thermal performance and environmental benefits (Yaman, 2021). Sarhan et al. (2013) discovered that plant-covered walls can reduce temperatures by 2 to 6°C compared to bare walls, demonstrating the ability of vegetated walls to enhance the thermal performance of building envelopes and serve as climate-adaptive façades to combat global warming. Furthermore, green façades can mitigate the



Figure 12: Green facade classification: a) Direct green facades, b) Double-skin green facades (Sheweka & Mohamed, 2012).

effects of the urban heat island (UHI) effect in urban areas, as vegetation absorbs radiated heat energy through evapotranspiration (Sheweka & Mohamed 2012).

Green facades comprise of climbing or hanging plants along the wall and can be classified as direct or indirect, as represented in figure 7 below. Direct green facades are when the vegetation is directly attached to the wall. Indirect green facades are when the vegetation is attached to a supporting structure, like a trellis, creating an air cavity subsequently adopting double-skin façade system characteristics (Manso & Castro-Gomes 2015).

Passive thermal control is achieved through vegetated facades in four ways: thermal insulation, interaction with solar radiation (shading), evaporative cooling, and variation of wind effects on the buildings (Sheweka & Mohamed, 2012). More advantages and associated disadvantages are identified in Table 10.

Table 10: Advantages and disadvantages of green facades (Sheweka & Mohamed 2012)

Feature	Advantages	Disadvantages
Temperature reduction	- Traps a layer of air within the plant mass. - Limits thermal transmittance	- The effectiveness is dependent on the amount and density of leaf cover.

	through thick vegetation mass. - Reduces ambient temperature via shading and plant processes of evapotranspiration. - The leaf cover can absorb or reflect solar radiation, good insulation to building envelope.	- Thermal bridging can occur due to the supporting structure
Building structure protection	- The foliage protects exterior finishes and structure from solar radiation and the elements. - Decreases the effect of wind pressure on building envelope	- Dependent on the density and coverage of the foliage, and the materials used for the structural components. - Maintenance of vegetated façades - Dependent on speed and direction of wind
Improved Indoor Air Quality (IAQ)	- Captures airborne pollutants such as dust and pollen. - Filters noxious gases and VOC's from building elements through bio-filtration and micro-organisms.	- Maintenance of vegetated façades - Coverage and density of the growing media
Noise reduction	- Reduce the sound levels that transmit through or reflect from the green façade.	- Dependent on the depth of the growing media, materials used for structural components and the overall coverage.
Surrounding external environment	- Influences urban hydrology by reducing the temperature of the building surfaces and improves the management of rainwater runoff. - Reduces the effect of the UHI in urban areas.	- Dependent on the density and coverage of the foliage, the irrigation system implemented and the drainage systems.

4.6 Methods used for assessing the thermal performance of facades

Attia et al. (2018), in their article "Current Trends and Future Challenges in the Performance Assessment of Adaptive Façade Systems," reviewed and analysed various publications to identify common methods for assessing the performance parameters of adaptive façades. Their findings indicate that computational simulation and experimentation are the primary methods used in this field.

Building performance simulations (BPS) are a crucial tool for assessing the thermal performance of adaptive façade technologies. These simulations are typically conducted during the design process to evaluate the energy efficiency and environmental impacts of proposed designs (Aksamija, 2015). Energy monitoring, facilitated through computational simulation, involves the collection and analysis of data related to energy use (Fitton 2013). BPS encompasses investigations into daylighting, passive ventilation, and thermal performance through detailed software modelling that predicts the behaviour of the building envelope (Ching & Shapiro 2020).

Computational simulations enable designers to investigate various design options and improve the thermal performance of building technologies. According to Fitton (2013), a building's energy use is influenced by three main factors: the building fabric, the systems and appliances within the building, and the energy consumption choices made by occupants. During the design phase, BPS helps refine the building design by examining trade-offs among these factors. Energy models are used to produce performance results for various components, such as walls, windows, façades, building shapes, and heating systems, as well as other schematic design parameters (Ching & Shapiro, 2020). These simulations provide insights into the future costs of energy use over the building's lifetime, enabling more informed design decisions (Ching & Shapiro, 2020).

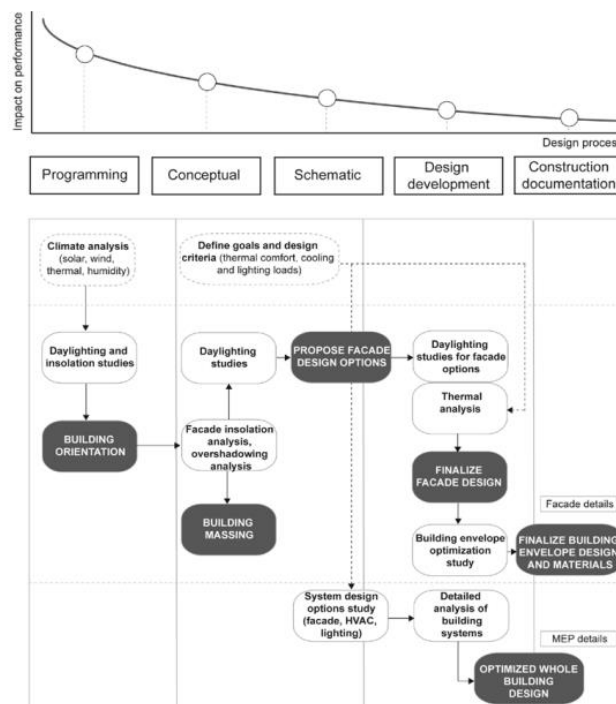


Figure 13: Framework developed by Aksamija(2015) for incorporating building performance procedures within the design process

4.7 Gaps in research

The theoretical framework was formulated through an extensive review of numerous research papers and academic sources, focusing on building technologies implemented as climate adaptive strategies to enhance the thermal amelioration potential of buildings in temperate climate regions. Despite the comprehensive review, several significant gaps in knowledge have been identified regarding the effectiveness and thermal performance of façades used as climate adaptation technologies temperate climates, especially within developing countries.

One major gap identified is the lack of detailed studies on the performance measures of façade systems when employed as climate adaptation technologies in temperate climate regions. Although building performance simulations are widely used, there is a notable deficiency in research concerning their application to various façade types and systems. More studies are needed to understand how different façade configurations perform under temperate climate conditions.

Additionally, there is an unexplored area concerning the use of building energy simulations to measure the thermal performance of adaptation technologies for retrofitting existing buildings, as opposed to new constructions. This research is crucial for developing effective strategies to improve the energy efficiency and thermal comfort of the existing building stock in response to climate change.

The study aims to address these knowledge gaps, specifically focusing on the discourse surrounding climate adaptation technologies in temperate climates. The primary objective is to analyse and assess the thermal performance of façades in the research sample, evaluating their façade strategies and the methods used to measure the performance and effectiveness of the implemented façade systems in temperate climate regions. Through the data analysis of the research sample group, the study seeks to bridge the existing knowledge gap while offering valuable insights into the potential benefits and challenges associated with implementing façade technologies in hot and temperate climate regions.

5. Results

5.1 Meta Study: The identified case studies

The data collected for this meta-study was selected based on the research sample group's Koppen Geiger climate classification, ensuring alignment with Tshwane's classifications: Cwb, Cwa, and Bsh (future climate classification). The sample group consists of 12 case studies, each demonstrating how façades, implemented as thermal adaptation technologies,

enhance the thermal performance of their respective building envelopes. These case studies illustrate the thermal amelioration potential of façade systems, comparing their optimal performance based on the measures discussed in section 4.5.3 of the study.

The results section provides a comparative analysis of the different case studies using the CMMO method addressed in section 3.6 of the study.

Table 11: The case studies which were analysed according to the performance of the façade as a climate adaptation technology.

No.	Building / Architect / year	Source Type
1	Manuel Gea Gonzalez Hospital / Elegant Embellishments / 2013	Architectural website
2	KMC Corporate Office / RMA Architects / 2012	Journal: STM Journal
3	Pearl River Tower /SOM / 2013	Article: CTBUH Research paper
4	78 Corlett Drive Building / Daffonchio Architects / 2018	Architectural website
5	Council House 2 / DesignInc / 2006	Architectural website
6	Podium AT Menlyn / Boogertman + Partners / 2012	Architectural website
7	The Grove / WOHA Architects / 2016	Architectural website
8	The Lantern / VTN Architects / 2016	Architectural website
9	Kadoori Biological Sciences Building, University of Hong Kong / Leigh and Orange Architects / 1999	Architectural website
10	National Biodiversity Pavilion / FREE & Fernanda Ahumda / 2022	Architectural website
11	Britam Towers / GAAP Architects and Urban Designers / 2018	Architectural website
12	University of Pretoria Plant Science Complex / KWP Create / 2012	Architectural website

5.2 CMMO based collection of the data.

The data collection method was structured according to the CMMO analysis framework, facilitating a systematic approach to data collection and analysis. This structured approach ensured that the collected data effectively addressed the research questions.

5.2.1 Context

The initial phase of data collection involved a thorough contextual analysis of the case studies. This analysis examined key factors including location, climate classification, building typology, and the number of stories in each case. By identifying the similarities and differences in each case study's contextual response, a deeper understanding of the individual façade performance can be deduced within each of the case studies.

Table 12: Contextual data collection of research sample group

Case Study No.	Name, architect and year	Location	Climate Region	Building Typology	No. Storeys
1	Manuel Gea Gonzalez Hospital / Elegant Embellishments / 2013	New Mexico / Mexico	Cwb	Hospital	Multi-storey
2	KMC Corporate Office / RMA Architects / 2012	Cyber City, Hyderabad/ India	Bsh	Commercial	Multi-storey
3	Pearl River Tower /SOM / 2013	Guangzhou / China	Cwa	Commercial	Multi-storey
4	78 Corlett Drive Building / Daffonchio Architects / 2018	Johannesburg / South Africa	Cwa	Commercial	Multi-storey
5	Council House 2 / DesignInc / 2006	Melbourne / Australia	Cwa	Commercial	Multi-storey
6	Podium AT Menlyn / Boogertman + Parners / 2012	Pretoria / Tshwane / South Africa	Cwb	Commercial	Multi-storey
7	The Grove / WOHA Architects / 2016	Guangzhou / China	Cwa	Residential / commercial	Multi-storey
8	The Lantern / VTN Architects / 2016	Hanoi / Vietnam	Cwa	Commercial	Multi-storey
9	Kadoori Biological Sciences Building, University of Hong Kong / Leigh and Orange Architects / 1999	Hong Kong / China	Cwb	Institutional	Multi-storey
10	National Biodiversity Pavilion / FREE & Fernanda Ahumda / 2022	Ciudad de Mexico / Mexico	Cwb	Institutional	Multi-storey
11	Britam Towers / GAAP Architects and Urban Designers / 2018	Nairobi / Kenya	Cwb	Commercial	Multi-storey
12	University of Pretoria Plant Science Complex / KWP Create / 2012	Pretoria / South Africa	Cwb	Institutional	Multi-storey

5.2.2 Mechanisms

The data collected from each of the 12 case studies is categorised according to the following categories: façade type, façade system, façade strategy, and material considerations. Each case study from the sample group is then analysed in relation to the concepts and information identified in the theoretical framework.

This approach effectively bridges the gap between theoretical concepts and practical applications. By categorizing the data in this manner, the study not only connects the

theoretical discussion from chapter 4 to real-life examples but moreover highlights the relationship between façade types, the systems implemented, and the corresponding façade strategies.

Table 12: Mechanisms data collection of research sample group

Case Study No.	Type of Façade	Active / Passive systems	Façade strategy	Material Considerations
1	Double-Skin Façade	Passive	A biomimetic facade made of Prosolve tiles, coated with titanium dioxide, was selected for its anti-microbial and de-polluting properties. This Prosolve370e skin acts as an urban filter, allowing natural light while blocking solar heat, reducing the need for artificial lighting and climate control. Additionally, it slows wind flow and disperses air pollutants across the panels (Architect Magazine, 2013).	- White Prosolve370e Thermoplastic tiles. Each lightweight, thermoformed plastic tile is coated with photocatalytic, air-scrubbing titanium dioxide (TiO ₂) powder is a nanomaterial patented by Cristal Global (Architect Magazine, 2013) -Steel substructure
2	Green Facade	Hybrid	The green facade is an energy-saving and visually impactful system that modulates light and air through the building. An integrated misting system in the aluminum trellis controls water release to the plants and cools the building's interior. This facade adapts both visually and functionally with the seasons: in summer, it limits solar radiation to keep the interior cool, while in winter, deciduous plants lose their leaves to allow more warmth inside. Additionally, this "powered by nature" facade provides acoustic insulation and protection from direct sunlight, heat, and dust (Singh & Nayak 2023).	-Aluminium trellis – modular and flexible (Singh & Nayak 2023). -Vegetated facade
3	Adaptative façade with integrated photovoltaic panels on sunshade devices	Active	Façade Design and Energy-Saving Principles: -Developed considering the city's solar and wind patterns (Seçluk & Ilgın, 2017). -Features a double skin system with an insulated	The exterior glazing is insulated, tempered glass with a low-E coating, while the inner glass skin is an operable clear glass panel for maintenance (Frechette & Gilchrist 2008)

			exterior layer, an interior layer, and an air space in between (Seçluk & Ilgin 2017) Ventilation and Solar Shading Devices: -Includes venting and solar shading devices within the cavity. -Motorized sunshades, controlled by photocells tracking the sun's position, provide solar shading and glare control, regulate daylight, moisture infiltration, and fresh air, and reduce solar heat gain (Seçluk & Ilgin, 2017; Frechette & Gilchrist, 2008). Photovoltaic System: -Integrated into the external shading and glass outer skin of Pearl River Tower. -Functions as both a building skin and a power generator, supplying electricity and shading the building (Seçluk & Ilgin, 2017; Frechette & Gilchrist, 2008). -Uses solar energy collected within the double façade for heating the building's dehumidification system (Frechette & Gilchrist, 2008). Thermal Regulation and Ventilation: -Externally ventilated double wall with low-E coated glass panels. -Serves as a thermal regulator and allows for mechanical ventilation of each floor (Frechette & Gilchrist, 2008).	
4	Adaptative façade	Active	Passive Shading System: -Highly efficient, consisting of fixed modular shading devices, protects occupants from harsh summer sun (ArchDaily, 2019). Sliding Shutters: Creates an ever-changing	The street interface facade features fixed shading louvers made of modular aluminium panels, attached to an aluminium frame using a clad-like construction method. This system is positioned in front of a curtain wall, resembling a

			appearance. Allows occupants to mechanically control the amount of natural light, heat, and glare entering the interior space (ArchDaily, 2019).	double-skin facade (ArchDaily, 2019). The adjacent dynamic facade system includes operable shading devices installed in the window cavities of the building envelope (ArchDaily, 2019).
5	Adaptative façade	Active	This nature-inspired façade moderates' climate with tapered ventilation ducts and daylighting strategies, integrated with an undulating concrete floor structure for heating and cooling (ArchDaily, 2013). It features a double-skin design with a timber outer skin for shading and a glazed inner skin for natural light and views, operated mechanically to regulate internal temperature through natural ventilation (ArchDaily, 2013). This dynamic facade exemplifies biomimicry, adapting the building in response to external conditions (MikePearce, 2016).	The facade consists of vertical timber slates covering a fully glazed curtain wall (MikePearce, 2016). These slates are mechanically operated and pivot vertically, adjusting their position based on the time of day and the angle of the sun (MikePearce, 2016).
6	Double-skin façade	Passive	Double skin façade with an air cavity acting as insulation against harsh temperatures. Since the top and the bottom of the outer glass façade are open, so when the cavity space starts to heat, the heat is pushed out bringing in a cool breeze inside the cavity space. (ArchDaily, 2013)	3 Different types of coloured glass are used for the façade. The laminate glass with a vinyl in between 2 pieces of glass (ArchDaily, 2013)
7	Green façade	Active	This green facade system incorporates vegetation into building exteriors, offering benefits such as enhanced air quality and thermal insulation. Key considerations encompass selecting appropriate plants, providing structural support, installing irrigation and drainage systems, facilitating maintenance access, integrating with building systems, addressing fire safety	Traditional plants that require less water (Xerophytes)

			concerns, and ensuring long-term sustainability through durable materials and minimal maintenance requirements (Cüce et al., 2021).	
8	Double skin façade	Passive	Double façade, the external façade provides breezes to freely move through the blocks in order to cool the building, the hollow design of the blocks allows minimum exposure to direct sunlight but allows adequate light in. This is an old traditional method used in Vietnam to cool buildings before air-conditioning systems were invented (Hoy & Hoy, 2021).	Double façade system of perforated terracotta blocks and curtain wall.
9	Double skin façade	Passive	The double skin façade includes an external glazed screen positioned 2.5 meters away from the building's outer wall. This space not only houses building services but also acts as an external buffer zone. It functions as a stack to direct hot air upwards, reducing solar heat gain. Open metal grilles on each floor allow for air circulation and provide access for maintenance (ibse.hk., 2001).	The building is adorned with silver grey ceramic tiles and a glass and steel double skin. Its north and south facades feature ceramic tiles and aluminium sun shading devices for window protection. The east and west facades incorporate double-skin glass curtain walls with multifunctional capabilities.
10	Adaptative façade system	Active	The building's lower level integrates views of endemic biodiversity, while upper levels feature a dynamic double façade of glass and multi-perforated aluminium. This design responds to interior lighting and ventilation needs, with thousands of movable 30x20 cm aluminium modules that react to climatic conditions, emphasizing its role in biodiversity evolution and sustainability (Alvarez, 2023).	The façade features movable 30x20 cm aluminium modules, while the building wall uses cantera, a volcanic stone native to the region. Additionally, aluminium fins run vertically along the facades, enhancing the static facade system (Alvarez, 2023).
11	Double skin façade	Passive	A prismatic 3D geometrical shape with Egg-Crate ceramic rods as a brie soleil for the curtain wall creates a majestic	The building utilizes EggCrate External Solar-Shading Systems. Terracotta Ceramic Rods are integrated into the

			aesthetic. Solar-shading systems, extending to the building's top, enable proper ventilation and thermal control while maximizing daylighting. These ceramic rods, a novel addition to solar-shading systems, are fixed atop the glass facade, providing year-round cooling by regulating solar radiation.	Egg-Crate Solar-Shading Systems. Horizontal Venetian Blinds are installed indoors to provide solar shading. Tinted blue glass is employed for shading interior spaces.
12	Green façade system	Passive	Passive design and energy efficiency principles were key in the building's design to enhance natural ventilation, solar control, and minimize heat gain and electrical consumption. Façade orientations were strategically chosen to optimize passive climate control using vegetated walls (gabion walls).	Two vertical rock walls with steel structures and mesh baskets containing rocks and planters for indigenous plants. Steel cylinder elements forming screens on the North and Western facades. Perforated textile reflectors with steel frames on the North and Western facades. Concrete louvres supported by steel frames on the northern facade.

5.2.3 Method

This data set identifies the methods used for measuring the performance of the building technology. These methods are consistent with those identified in section 4.6. However, it was observed that several case studies in the grey literature provided little to no information about the methods used to measure the performance of the building technology. Table 12 lists the case studies that include information about these methods and describes their execution, if such descriptions were published.

Table 12: Methods for measuring the effectiveness of facades

Case Study No.	Method for Measuring Effectiveness
1	The success of the façade was checked using computation simulation (Architect Magazine, 2013).
2	N/A
3	Computational simulation using an energy model (Frechette et al, 2008)
4	Computational and empirical methods (Arch daily, 2019)
5	Computational simulation through generating an energy model of the building in the design stages (ArchDaily, 2013)
6	N/A
7	N/A
8	N/A
9	N/A
10	N/A

11	N/A
12	N/A

5.2.4 Outcomes

The dataset below captures qualitative information about the recorded achievements, benefits, and constraints of the facades in each case study. The recorded achievements highlight the success of the façade strategy as published in the associated grey literature and academic sources. The benefits section organizes qualitative data according to the addressed or achieved performance indicators listed in section 4.5.3. Additionally, the constraints associated with the employed facades are also documented. This structured approach enables a comprehensive analysis of the façade technology considering both their benefits and limitations.

Table 13: data set identifying the recorded achievements, benefits and constraints

Case Study No.	Recorded Achievements	Benefits	Constraints
1	It was recorded that the façade eliminates the equivalent amount of NO produced by 1000 vehicles (Architect Magazine, 2013).	Thermal comfort - Regulated indoor temperature (Architect Magazine, 2013). -Daylight control -Decrease solar glare Air quality -Cleaner air introduced into the interior spaces of the building. -absorbing air pollutants, improving the exterior air quality surrounding the building. -Urban filter Energy Efficiency - Filters natural light, decreasing the need for artificial light throughout the course of the day. - Lowered requirement for mechanical ventilation and cooling equipment. Technical considerations - Ease of installation – lightweight panels - Ease of assembly - panels are assembled like puzzle pieces (Architect Magazine, 2013).	Technical constraints - The static nature of the double facade limits the facades adaptability to future climate variations and changes. Operational constraints - The panels are calculated to absorb air pollutants equivalent to 1000 vehicles per day. If there are an increased number of vehicles in the vicinity, this will impact the internal air quality of the building due to the inability of these panels to handle the overload of pollutants. Maintenance constraints - the TiO₂ material sprayed onto the thermos-plastic modules wears thin over time and needs to be reapplied - maintenance constraint. Cost Constraints - TiO₂ material is patented, the availability as well as feasibility are concerns which must be addressed.

2	N/A	Thermal comfort - Decreases thermal gains into the building - limits direct sunlight exposure - The foliage absorbs UV, reducing solar transmission - Regulates indoor temperature using evapotranspiration. - Creates ambient internal temperature during winter months reduces solar glare Daylight and glare -Filters natural light, reducing glare Air quality - The vegetation attracts the dust particles in the air, improving IAQ. -Evapotranspiration Energy Efficiency - Filters natural light, decreasing the excessive use of artificial light throughout the course of the day. - Lowered requirement for mechanical cooling and ventilation equipment. Biodiversity benefit - Increasing the biodiversity in urban contexts. Technical considerations - Ease of installation – modular lightweight panels - Ease of assembly – lightweight panels -The modularity of the individual aluminium panels allows for flexibility in assembly and design.	Operational constraint - Different plant species have different water requirements. this consideration must be made when grouping plants together. - The misting system used for irrigation, does not allow for the water runoff to be captured and filtered back into the system - resulting in water wastage. Maintenance concerns - Plants require regular maintenance (i.e.. pruning, pest control etc)
3	The building uses 30% less energy compared to buildings of a similar magnitude. The building envelope produces 1% net energy required to operate the building	Thermal comfort - Automated shading system reduces the solar heat gain for the interior space of the building and reduces solar glare - The air cavity is mechanically ventilated, improving indoor air	Technical constraints - The 200mm cavity imbedded in the double skin façade poses accessibility issues for maintenance. Cost constraint

	(Frechette & Gilchrist 2008)	temperature - Heating and cooling loads are reduced at the perimeter of the building - Improved thermal performance. Daylight and glare - Brings useful daylight into the interior space. - Reduces direct glare into the building through an automated shading system. Acoustic comfort - Reduced noise transmission from the outside of the building to the inside (Frechette et al, 2008). Air quality - The mechanical ventilation system within the cavity, provides improved IAQ - Dehumidification system which uses heat collected from the double wall facade as an energy source to power the mechanised dehumidification system for the building (Frechette et al., 2008). Ventilation - The 'de-coupled' ventilation system within the cavity, provides improved air quality and air exchange effectiveness, improving the indoor air quality of the building (Frechette & Gilchrist 2008) Energy Efficiency - Reduction of the extensive use of mechanical cooling and ventilation equipment - Reduction of artificial lighting - electrical energy is produced through the integrate BMI Technical considerations - The BMI automatically controls interior conditions, optimising occupant thermal comfort	-The cost of the implemented façade system is of concern. It poses investment issues and implementation constraints for developing countries
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4	N/A	Thermal comfort - Decrease thermal gains into the building by limiting direct solar exposure - Natural light which enters the building can be adjusted by the occupants - Decreases glare that enters the interior space - Passive ventilation methods improving indoor air temperature Daylight and glare - The passive shading system is mechanically operated affording the occupants to adjust the amount of daylight that enters the space and reduce solar glare. Acoustic comfort - Reduces noise transmission from exterior environment. Air quality - Improved IAQ due to passive ventilation strategies Ventilation - The passive shading system and the fixed modular aluminium-clad facade acts as an external skin for the curtainwall system, allowing for natural air to enter the building and for stale air to exit the building. Energy Efficiency - Decrease the amount of artificial light needed throughout the course of the day - Decrease the constant needed for mechanical cooling and ventilation equipment Technical considerations - There are two facade types employed to achieve thermal performance. - Due to the modular nature of	Technical constraints - The static nature of fixed modular facade limits the facades adaptability to future climate variations and changes. - Due to the street façade being fixed, it makes it difficult to clean the inner skin curtainwall system. Cost Constraints - The integrated dynamic system for the façade poses feasibility concerns for investors.
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		the facade system, maintenance and replacing panels of the facade is made easier.	
5	Reduction of the building's energy consumption by 50%, gas consumption by 87% and main water supply by 72% is recorded (ArchDaily, 2013).	Thermal comfort - Thermal regulation of internal space -Solar control, by means of solar shading system, reduces thermal transmission and solar glare. -Passive ventilation methods improving indoor air temperature -Introduction of natural light into interior space Daylight and glare - Dynamic shading systems reduce solar glare and maximise natural light according to the sun path. Air quality - Improved IAQ as the building receives a fresh air change every half hour (MikePearce, 2016). This is because of the wind turbines on the building crown enhances air movement and passive ventilation throughout the building. Ventilation -Stack ventilation method which is facilitated by active measures. Energy Efficiency - Decrease the amount of artificial light needed throughout the course of the day - Decrease the constant needed for mechanical cooling and ventilation equipment Technical considerations - Sophisticated engineering within the building, including the use of timber slats, wind turbines, automatic shutters, shower towers, and a phase change apparatus for water cooling. - Recycled wood is used for the	Technical constraints - The use of thermal mass to absorb heat may necessitate specific materials and construction techniques, potentially increasing construction complexity. Operational Constraints - The timber vertical slats system must be durable and weather-resistant, and its automated operation needs to be reliable to avoid malfunction. Maintenance constraint - Recycled timber shading system operational system Cost constraint - Using recycled wood and other sustainable materials may limit material availability and increase procurement costs.

		building's automatic shutters, aligning with sustainability principles.	
6	N/A	Thermal comfort -Thermal control strategies regulate indoor temperature -Passive ventilation methods improve indoor air temperature -Vinyl in glass assembly reduces solar glare Daylight and glare -The glass assembly reduces solar glare and maximises natural light into the building. Acoustic comfort -Sound barrier to reduce noise transmission (ArchDaily, 2013) Ventilation -Passive ventilation strategy – stack ventilation method Energy efficiency -Reduction of extensive use of artificial lighting throughout the day due to the daylighting benefit of the façade system -Reduction of mechanical ventilation equipment (ArchDaily, 2013)	Cost constraints -Glass assembly poses cost concerns
7	N/A	Thermal comfort -Reduction of solar glare -Reduced solar radiation and evapotranspiration improves indoor temperature Daylight and glare -Solar blocker, reducing solar glare (Cüce et al., 2021). Air quality -Improved IAQ by means of evapotranspiration (Cüce et al., 2021). Biodiversity benefit - Increasing the biodiversity in urban contexts.	Maintenance constraint -vegetation on façade require constant maintenance Operational constraint - Different plant species have different water requirements. this consideration must be made when grouping plants together.
8	N/A	Thermal comfort -Passive ventilation methods	Technical constraints -There may be challenges

		improve indoor air temperature -Reduces solar glare Air quality -Improve indoor air quality through passive ventilation strategies Ventilation -Passive ventilation strategies – stack ventilation method Energy efficiency -- Decrease the amount of artificial light needed throughout the course of the day - Decrease the constant needed for mechanical cooling and ventilation equipment (Hoy & Hoy, 2021).	with the durability of the terracotta blocks Cost constraint -The cost of custom making the terracotta blocks
9	Savings of 53,360 kWh of energy per year (ibse.hk., 2001).	Thermal Comfort -Reduction of solar radiation through façade -Passive ventilation methods improve indoor air temperature Air quality -Improve indoor air quality through passive ventilation strategies Ventilation - Passive ventilation strategy – stack ventilation method	Technical Constraints -Adaptability to varying climate conditions
10	N/A	Thermal comfort - Passive ventilation methods improve indoor air temperature -decreases direct solar exposure -limits solar glare Improves daylight entry into building Daylight and glare -The façade system unfolds in response to the lighting needs of the interior spaces, reducing solar glare Air quality -Improved indoor air quality through passive ventilation strategies	Maintenance constraint -High cost required to maintain the effectiveness of the adaptative façade system. Cost Constraint -The implemented dynamic system provides a cost constraint due to its complexity

		Ventilation -Passive ventilation strategy: stack ventilation method through the air cavity Technical consideration -wind operates the shading devices	
11	N/A	Thermal comfort - Regulates the indoor temperature, ensuring the temperature of 25°C is obtained all year round. -Reduces solar glare Daylight and glare -Reduces the amount of direct solar glare into the building -The solar shading system maximise daylight into the building Energy Efficiency -Reduces the excessive use of artificial lighting	Technical constraint -Adaptability to varying climate conditions. Maintenance constraint -Clay rods pose a maintenance and longevity concern.
12	N/A	Thermal Comfort - Improved indoor air temperature Acoustic comfort - Absorbing noise and providing sound insulation for interior spaces. Air Quality -Improved IAQ due to evapotranspiration Biodiversity benefit - Increasing the biodiversity in urban contexts.	Technical constraints -Green façades pose many challenges in terms of appropriate construction methods, plant selection. -Adaptability to varying climate conditions. Operational constraint - Different plant species have different water requirements. this consideration must be made when grouping plants together.

6. Discussion

The data collection process was conducted through a desktop study, and the analysis of the building façades and their systems is presented below. Using the CMMO analysis framework, the following aspects were examined: the building's name, designer, year of construction, number of floors, location, climate classification of the region, implemented

mechanisms, and outcomes. This analysis aims to deduce the thermal performance and amelioration potential of facade technologies in temperate and hot climatic regions.

6.1 Context discussion

The case studies, as stipulated in the methodology section, were identified according to their Köppen-Geiger climate classifications: Cwb, Cwa, and Bsh. Beyond this prerequisite, the case studies also shared other commonalities, such as the number of stories and the building typology, encompassing mainly high-rise commercial buildings and institutional facilities. . Despite these similarities, the case studies exhibit contextual diversity due to their differing locations across various continents, including Africa, Asia, South America, and Australia.

It can be observed in the data sets that the case studies adopt different façade technologies due to their contextual diversities, demonstrating the effectiveness and versatility of façade systems as thermal adaptation strategies for building envelopes across various typologies in temperate and hot climatic regions globally. The success in responding to climate change is related to the ability to acknowledge and act in accordance with its complexity and dynamics (Kosanovic et al., 2018). Therefore, the case studies substantiate the global adaptability and versatility of façade technologies in responding to climate change.

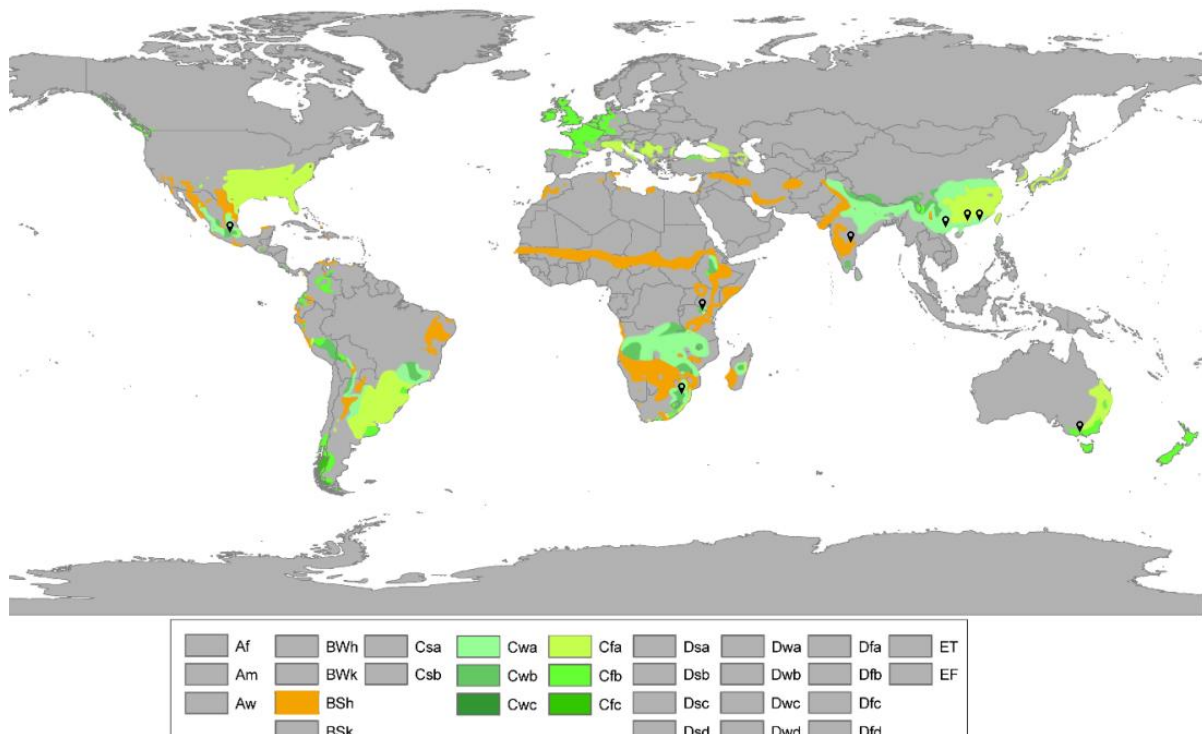


Figure 14: World map identifying the locations of the chosen case studies relative to their climate classification (Author, 2024).

6.2 Mechanism Discussion

In the framework of the sample group, façade design decisions for different façade configurations were evaluated and general inferences were made in relation to the mechanisms implemented and the material make-up of the technology. The analysis of the employed façade system involved several steps. First, it required defining the type of façade configuration used and identifying if the façade system is of active, passive or hybrid nature. Once the system configuration was deduced, the second step required a comparison of the system configuration to its relative benefits and constraints, which was obtained from the outcomes section of the study – section 4.2.4. These steps were essential in understanding the mechanisms behind each façade systems approach in relation to the relative benefits and constraints. The table below encapsulates this comparative approach discussed above.

Table 14: Façade systems in relation to the façade types and characteristics

Case study	Façade type	Climate region	Active systems	Passive systems	Hybrid systems	Benefits
1	Double-skin façade	Cwb				4
2	Green façade	Bsh				6
3	Adaptive façade	Cwa				7
4	Adaptive façade	Cwa				7
5	Adaptive façade	Cwa				6
6	Double-skin façade	Cwb				5
7	Green façade	Cwa				4
8	Double-skin façade	Cwa				4
9	Double-skin façade	Cwb				3
10	Adaptive façade	Cwb				5
11	Double-skin façade	Cwb				3
12	Green façade	Cwb				4

6.2.1 Façade systems

The performance of the façades in the research sample group hinges on the interplay between 3 systems: active, passive and hybrid systems. When considering the efficiency of façade technology, various systems are employed to meet different thermal requirements

(Yaman, 2021). Each case study employed either active, passive or hybrid systems into the façade configurations.

Most case studies employed passive systems, followed by active systems, with hybrid systems being the least favoured. Passive systems were commonly found in double-skin façades, while adaptive façades utilized active systems. Green façades employed hybrid systems, integrating passive elements to ameliorate thermal capacity and active components to water the vegetated façades.

The data also revealed that passive systems were predominantly implemented in Cwb climate regions, characterized as temperate with dry winters. In contrast, Cwa climate regions, classified as humid subtropical, primarily used active systems. Passive systems enhance a façade's heat-insulating capacity without relying on artificial energy sources (Zhou et al., 2021) and are less effective in year-round humid conditions typical of Cwa regions. Active systems, supporting passive design strategies, are more suited to manage these varying climate conditions (Yaman, 2021). Additionally, hybrid systems were implemented in hot steppe climate regions (Bsh), showcasing their capability to handle extreme temperatures. Green façades in Bsh regions achieved passive thermal control through thermal insulation, evaporative cooling, and shading, thereby reducing direct solar radiation (Sheweka & Mohamed, 2012).

Case studies that employed active systems demonstrated better thermal benefits due to the adaptable characteristics intrinsic to active systems. These systems can adjust to varying climate conditions, optimizing the thermal performance of the façade configurations (Yaman, 2021).

6.2.2 Double-skin façade strategies

Most double-skin facades in the research sample group consist of internal glazing, a air cavity and an external skin – glazed or opaque. The thermal efficiency of double-skin façades in the research sample group is primarily due to the air cavity. This is because the air cavity creates a thermal buffer between the internal and external environments (Aksamija, 2013), reducing solar transmission through the façade, protecting the interior environment from solar heat gain (Aksamija, 2015). Additionally, the air cavity is used to passively remove heat from the building through an air flux driven by the buoyancy effect (Quarrie & Bakirhan, 2023).

6.2.3 Adaptive façade strategies

Adaptive façades (AF) are the external skins of building envelopes designed to adapt to changing boundary conditions by incorporating transient characteristics in their design (Soudian & Berardi, 2020). In the research sample group, adaptive façades implement mechanically operated solar control devices and facilitate passive ventilation in the façade's air cavity to achieve the following thermal strategies:

- Solar Control: Managing the amount of solar radiation entering the building to optimize thermal comfort and energy efficiency.
- Reduction of External Heat Gains: Minimizing the heat absorbed from the external environment to reduce cooling loads.
- Maximizing Daylight While Minimizing Glare and Direct Solar Radiation: Allowing natural light to penetrate the building while preventing glare and reducing direct solar radiation on the inner glazed skin.
- Reduction of Thermal Heat Gains: Lowering the overall thermal load on the building by controlling heat transfer through the façade.

It is evident that adaptive façades enhance the façade's ability to respond dynamically to environmental conditions, improving the building's thermal performance and occupant comfort. Furthermore, it was noted that some case studies implemented BMI systems to automatically control indoor thermal conditions by adapting/responding to external climate conditions.

6.2.4 Green façade strategies

The integration of vegetation on buildings through vertical greening, such as green façades and living walls, significantly enhances the building's thermal performance and provides numerous environmental benefits (Yaman, 2021). This is evident in the green façades implemented in the research sample group, where thermal efficiency is achieved through the following strategies:

- Reduction of Thermal Heat Gain through Evapotranspiration: Vegetated façades cool the air around them by releasing water vapor, thus lowering the temperature of the building envelope.
- Solar Control: The vegetation reduces the amount of solar radiation reaching the building's interior, thereby lowering cooling loads and improving indoor thermal comfort.

Additionally, green façades contribute to increased biodiversity in urban areas and help mitigate the Urban Heat Island (UHI) effect on a micro-scale. They provide shade to heat-absorbing surfaces and facilitate evapotranspiration, both of which contribute to cooling the surrounding environment (Sheweka et al., 2012). This dual role of improving thermal performance and enhancing urban biodiversity underscores the multifaceted benefits of green façades in sustainable building design.

6.2.5 Material considerations for façade technologies

The selection of materials is a crucial factor in designing façades (Aksamija, 2015). Materials can significantly enhance the thermal performance of the building envelope by minimizing thermal bridging, strategically using thermal mass, and decreasing thermal gains (Aksamija, 2013). Although the grey literature does not clearly identify the thermal impacts of material selection on façade technology, the following observations from the data set can be made:

- Case Study 1: Employed thermoplastic as the outermost skin of the double-skin façade. This thermoplastic screen acts as a brise-soleil, serving as an urban filter and absorbing solar radiation to reduce solar heat gains through the glazed second skin. This indicates the material's thermal resistance to heat transfer (Aksamija, 2013).
- Case Study 8: Utilized a similar façade strategy, opting for a terracotta brise-soleil for the external skin of the double-skin façade. Terracotta clay blocks are known for their excellent thermal mass properties, which enable them to absorb, store, and release heat energy, thereby reducing indoor temperature fluctuations (Nadoushani et al., 2013).
- Case Study 6: Incorporated triple glazing in the external curtain wall, which included vinyl in its assembly. The vinyl layer protects the interior environment from direct solar radiation and glare, thus reducing solar transmission.
- Case Study 4: Used recycled timber slats for automated solar shading devices. Choosing timber over aluminium or steel highlights a deliberate thermal design strategy by the architect. Unlike metals, timber is not conductive and therefore eliminates thermal transmission from the solar shading devices to the façade skin.

These case studies illustrate the diverse ways in which material selection can impact the thermal performance of façades, even if such impacts were not explicitly detailed in the grey literature.

6.3 Method Discussion

In section 4.6 of the study, methods for measuring the thermal performance of façade technology is discussed. Computational simulation methods were identified as the tool to measure the thermal performance of a façade. Computational simulations enable designers to investigate various design options and improve the thermal performance of building technologies (Fitton, 2013). What is evident from the research sample is that there was a lack of computational simulation for energy modelling made across the sample group as evidenced in Table 15.

Table 15: Façade types, methods and recorded achievements

Case study	Façade type	Façade system	Method measuring	recorded for thermal	Recorded achievements
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			performance of façade technology	
1	Double-skin façade	Passive	Computational method	It was recorded that the façade eliminates the equivalent amount of NO produced by 1000 vehicles (Architect Magazine, 2013).
2	Green façade	Hybrid		
3	Adaptive façade	Active	Computational method-energy model	The building uses 30% less energy compared to buildings of a similar magnitude. The building envelope produces 1% net energy required to operate the building (Frechette & Gilchrist 2008)
4	Adaptive façade	Active	Computational method	
5	Adaptive façade	Active	Computational method-energy model	Reduction of the building's energy consumption by 50%, gas consumption by 87% and main water supply by 72% is recorded (ArchDaily, 2013).
6	Double-skin façade	Passive		
7	Green façade	Hybrid		
8	Double-skin façade	Passive		
9	Double-skin façade	Passive		Savings of 53,360 kWh of energy per year (ibse.hk., 2001).
10	Adaptive façade	Active		
11	Double-skin façade	Passive		
12	Green façade	passive		

Two interesting observations emerge from the above table. First, the majority of façade technologies that incorporated computational methods to measure the thermal performance of the façade recorded significant achievements. Second, most of the case studies that implemented adaptive façade technologies identified methods to measure thermal performance. This finding aligns with the research by Attia et al. (2018), which deduced that computational simulation methods are effective for measuring the thermal performance of adaptive façades.

6.4 Outcomes discussion

6.4.1 Recorded benefits

Kristl (2020) suggests that the adaptive capacity of a system can be monitored and measured according to design effectiveness and local resilience indicators (Kristl et al., 2020). In section 4.5.3 of the study, the performance indicators of a façade are identified as follows:

- Thermal comfort
- Daylight and glare
- Acoustic comfort
- Air quality
- Ventilation
- Energy efficiency

The performance of the façades in each case study is analysed based on these parameters to determine their thermal effectiveness. The cumulative performance of each façade system, based on the criteria suggested by Kristl et al., (2020) indicates the adaptive capacity of the façade system. Through this analysis process, a relationship can be observed between the performance measures and the adaptive capacity of a façade system. Consequently, these performance measures serve as indicators of the degree of adaptive capacity of a façade system.

Table 16: Façade benefits

Case study	Thermal comfort	Daylight and glare	Acoustic comfort	Air quality	Ventilation	Energy Efficiency	Technical consideration	Biodiversity
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								

6.5 Benefits vs Methods vs Constraints

A detailed analysis of the outcomes is conducted in section 5.2.4 of the study. In section 5.2.2 of the study, the relationship between the method for measuring the effectiveness of the façade strategy and the outcome is deduced. The focus of this discussion will build on that analysis made from the findings, with specific focus on three key categories (these categories include pertinent factors which were discussed in the above-mentioned sections). The first category takes into consideration if there was a method used to measure the

effectiveness of the façade system. The second category considers the façade systems which have employed more than four benefits. The last category will consider the façade systems that exhibit less than two constraints. These categories and the respective outcomes are presented in the table below. The cells that are highlighted in orange, signify the respective outcomes.

Table 17: Benefits vs Methods vs Constraints

Case study	Façade system	Method for measuring effectiveness incorporated	More than 5 benefits	Less than 3 constraints	Total
1	Double-skin facade				1
2	Green facade				2
3	Adaptative facade				3
4	Adaptative façade				3
5	Adaptative façade				2
6	Green facade				2
7	Green façade				1
8	Double-skin façade				1
9	Double-skin façade				1
10	Adaptative façade				2
11	Double-skin façade				1
12	Green facade				1

The research findings, depicted in Table 17, demonstrate a clear trend: adaptive façades (AFs) exhibit more promising results, with numerous benefits and minimal constraints. Furthermore, the adaptive façades in the research sample group have incorporated methods to measure their effectiveness. Consequently, adaptive façades are recorded as yielding the best results, leading to better thermally performing buildings. AFs can regulate energy and mass flow through reversible changes in their properties, achieved through advanced technologies and components (Attia et al., 2018).

7. Conclusion

This study employs a pragmatic approach to qualitative research, utilizing a meta-study research method to conduct an in-depth inquiry into climate adaptation in the built environment within a real-life setting (Yin, 2018 in Saunders et al., 2019:196). This approach facilitates an understanding of the complex dynamics at play, examining the phenomenon

within its real-life context and recognizing that the case itself is inseparable from these dynamics (Groat & Wang, 2013). The dual aims of this study are to address the broader issue of climate change within the built environment and to determine the current and long-term thermal adaptation response of building technologies, implemented both locally and globally, to enhance the thermal adaptation of buildings in the City of Tshwane.

A qualitative research method structured around a systematic literature review was employed for data collection and analysis. This method entailed investigating grey literature, including journal articles and research papers, and adopting a relational epistemology focusing on sourcing real-life examples both locally and globally. The study analysed and compared the relationships between these examples, recognizing that the ontology of the study is non-singular (Kivunja and Kuyini, 2017), as the analysis of the case studies is subject to individual interpretation.

The selected case studies, categorized by Köppen-Geiger climate classifications (Cwb, Cwa, and Bsh), demonstrate diverse façade systems including passive, active, and hybrid configurations. Despite similarities in building typology and number of stories, regional climates significantly influence façade system choices. This highlights the global adaptability of façade technologies across continents such as Africa, Asia, South America, and Australia in responding to climate change complexities and dynamics (Kosanovic et al., 2018).

Analysis of façade systems in the research group reveals passive systems are prevalent in double-skin façades in temperate Cwb climates, while humid subtropical Cwa climates favour active systems. Hybrid systems, less common but effective in hot steppe Bsh regions, combine passive thermal control with active elements, particularly in green façades. Strategic material choices—like thermoplastics, terracotta, triple glazing with vinyl, and recycled timber—optimize thermal performance by minimizing thermal bridging, utilizing thermal massing, and reducing thermal gains.

The study underscores the role of computational simulation in evaluating façade technologies' thermal performance. Case studies employing these methods, particularly in adaptive façade technologies, report significant achievements, consistent with findings by Attia et al. (2018). Performance indicators—thermal comfort, daylight and glare control, acoustic comfort, air quality, ventilation, and energy efficiency—measure façade systems' adaptive capacity to environmental changes, reflecting their effectiveness.

Detailed outcomes analysis in section 5.2.4 highlights adaptive facades' superior results, boasting numerous benefits with minimal constraints. These façades excel in managing energy and mass flow through reversible property changes, leveraging advanced technologies and components (Attia et al., 2018). Their flexibility and resilience make adaptive façades an optimal choice for urban buildings in diverse climates, enhancing sustainability and resilience.

In conclusion, the study findings indicate the effectiveness of adaptive façade technologies in improving thermal performance and responding to climate change challenges. By integrating advanced materials, strategic design approaches, and computational simulations, adaptive façades can significantly enhance urban building sustainability in temperate and hot climates. This research contributes to advancing climate adaptation technology discussions and aims to enhance urban living standards by addressing climate change impacts within the built environment.

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