FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGHRISE OFFICE
I. ACKNOWLEDGEMENT

First I would like to thank my mentors for their support from the very beginning; Arie who was always providing me with simple and effective solutions. Without the help of Eric it wouldn’t be possible to deal with the size of the project. His expertise in the bioclimatic field and the thrive for simple innovations. Special thanks to Alejandro who was always there putting me back in track and the setting of boundaries.

I would like to express my gratitude to Boris Kock who gave me the insight from the facade industry and the simplicity of unitized curtain wall systems. Our meeting was very helpful in order to realise the real practice of façades.

I am also grateful to Claudio Vásquez, Tillmann Klein, Ullrich Knaack and especially Ignacio Fernández, who provided me with a lot enthusiasm to start in the field of facades. “Simplicity is the solution for every situation”, and with his passion work looks more like hobby.

However, the whole trip of this thesis would not be the same without my family and close friends. Special thanks to Ana who was always patient and supportive, my housemates and friends who I couldn’t see as much last few months.

Most importantly, I would like to deeply thank my parents for always listening and the help they were always giving me.

Without the contribution of all these people this thesis would not be possible.
# CONTENTS

1. Acknowledgement .................................................................................................................. 3

1. Introduction .............................................................................................................................. 11

1.1. Problem statement ............................................................................................................... 12

1.2. Main Objectives .................................................................................................................. 16

1.3. Research Questions ............................................................................................................. 17

1.4. Sub questions ....................................................................................................................... 17

1.5. Approach and methodology ............................................................................................... 17

1.6. Scheme of thesis ............................................................................................................... 19

2. High-rise .................................................................................................................................. 21

2.1. History .................................................................................................................................. 22

    Chicago .................................................................................................................................. 22

    New York City ....................................................................................................................... 23

    Singapore ................................................................................................................................ 24

2.2. Space efficiency .................................................................................................................... 25

    Structural efficiency and floor slab size .............................................................................. 26

    Floor to floor height ............................................................................................................. 27

2.3. Ventilation modes .................................................................................................................. 27

    Passive mode ........................................................................................................................ 27

    Mixed-Mode ........................................................................................................................ 28

2.4. Conclusion on high-rise ........................................................................................................ 31

3. Climate & cooling ..................................................................................................................... 33

3.1. Climate zones ....................................................................................................................... 34
Sub-tropical vs Tropical climate ........................................................................................................ 35
Possible climate change ......................................................................................................................... 35

3.2. Passive and active cooling strategies ............................................................................................... 36
Passive cooling techniques ....................................................................................................................... 37

3.3. Characteristics of the local climate in Singapore ............................................................................. 41
Location .................................................................................................................................................. 41
Metrological data ................................................................................................................................... 42
Potential cooling techniques for Singapore .............................................................................................. 46

3.4. Conclusion on local climate ............................................................................................................. 49

4. Thermal Comfort .................................................................................................................................. 51

4.1. Thermal sensation ............................................................................................................................... 52
Heat transfer of the human body ................................................................................................................. 52
Factors in thermal comfort ....................................................................................................................... 54

4.2. Predicting thermal comfort ............................................................................................................... 58
Theory of Fanger ...................................................................................................................................... 58
Thermal comfort indexes .......................................................................................................................... 59

4.3. Conclusion on thermal comfort ........................................................................................................ 66

5. Natural Ventilation ............................................................................................................................... 69

5.1. Principles of natural ventilation in a high-rise building ..................................................................... 70
Natural ventilation strategies .................................................................................................................... 71

5.2. Design considerations ....................................................................................................................... 72
Climate .................................................................................................................................................... 73
Building design ...................................................................................................................................... 79
1. Cross & stack ventilation design tool .......................................................... 217
2. Design results ......................................................................................... 226
3. Interview façade builder Scheldebouw ................................................. 236
4. Architecture .......................................................................................... 240

Appendix E. Reference projects ................................................................. 243
1. Brise Soleil ............................................................................................. 243
2. Monsoon window ................................................................................... 248
3. Wind improved designs ......................................................................... 250
4. Solar chimney ......................................................................................... 251

Appendix F. Extra ..................................................................................... 254
1. Daylight ................................................................................................. 254

III. References .......................................................................................... 265
IV. Curriculum Vitae ................................................................................ 273
1. INTRODUCTION

Definition **SKYSCRAPER**: “A skyscraper is defined as a multi-story building whose architectural height is at least 100 meters. This definition falls midway between many common definitions worldwide, and is intended as a metric compromise which can be applied across the board worldwide.” (Emporis)

Definition **SUPERTALL** building: a building with a minimum height of 300 meters (Gabel et al., 2016).

Definition **TALL OFFICE** building: an office building 100 to 300 meters high, occupied during regular work hours from 9:00 – 18:00 with office functions.

**HIGH-RISE OFFICE** building is a synonym for tall office building, with similar height and function requirements.
1.1. Problem statement

The thrive towards high-rise structures is increasing in the last decades. Densification, population growth, technological innovations and globalization are important drivers for the transformation of urban areas.

Densification

Increasing density in cities is now widely accepted as necessary for achieving more sustainable patterns of life to reduce energy consumption and to combat climate change. The concentration of people in denser cities sharing the space for infrastructure and facilities offers much greater energy efficiency than the expanded horizontal city. Less land is used as well as more intensive use of the infrastructure and mobility.

Figure 1.1 The amount of 200 m+ buildings completed each year from 1960 to 2015, with projections till 2017 (Gabel, Carver, & Gerometta, 2016).
A forecast of about 70% of the world’s projected nine billion inhabitants will be urbanized by the year 2050, up from 51 percent of seven billion urbanized in the year 2010. This will increase the amount of people living in cities by 2.8 billion people over the next 40 years (Wood & Salib, 2013). Given the scale of these population shifts, the vertical city is increasingly as a viable solution for many urban centres.

There are many energy benefits from tall buildings. In addition to the large-scale benefits of density versus horizontal spread, tall buildings offer advantages such as less materials needed for square meter area for heat loss/gain and less distance to destination. The potential of harvesting wind and solar energy at height and the possibility to have public space on the roof.

High-rise trend

Recent years have seen a boom in tall building construction unprecedented in terms of its global scale, with more and taller high-rise buildings being constructed than ever before (Gabel et al., 2016). In figure 1.1 we can see an exponential grow in high-rises above 200 meters, and even the supertall buildings 300m+ show a growing trend. With inventions and improving technologies it is possible to build buildings over 800 meter high, Burj Khalifa, Dubai, counts 828 meters. In 2015 the tallest building constructed is the Shanghai Tower with 625 meters (Gabel et al., 2016).

![Figure 1.2 Tallest buildings in the world (Emporis).](image)

In today’s context, with climate change arguably the greatest challenge of the modern world, it is well known that the built environment is a significant contributor to global greenhouse gas emissions, with buildings accountable for 30–40% of all primary energy used worldwide and carbon dioxide emissions in buildings increasing at an annual rate of 2% between 1971 and 2004 (Oldfield, Trabucco, & Wood, 2009). A significant amount of the electricity consumed in office buildings goes towards fully air-conditioned commercial and institutional buildings. The situation is even more alarming in the case...
of tall buildings where greater energy consumption is required to provide comfort (Liu, Ford, & Etheridge, 2012).

Tropical climate zone

The tropics are defined as the belt that is centred around the Earth’s equator, between the Tropic of Cancer and the Tropic of Capricorn (each 23.5° of latitude off the equator). Although tropical regions vary considerably, they are warm and have small changes in daily temperatures. These geographic and environmental commonalities play a key part in the local architecture and culture in the region. Currently about 40% of the world’s population is living in the tropical climate zone (Clark, Gertler, & Feldman, 2003).

Figure 1.3 Locations of tropical climates, with subtypes. 40% of world population lives in the tropical climate (Source: https://en.wikipedia.org/wiki/Tropical_climate).

Rapid population growth, coupled with economic growth, means that the region’s influence will grow in coming decades. At the same time, tropical conditions are expanding as a result of climate change. Population in the tropical zone is expected to exceed that of the rest of the world in the late 2030s, confirming the importance of the Tropics for the world’s future.

Singapore

The city-state island is reliant on fossil fuels and due to its high standards it is a representation for dense urban areas in the tropical climate zone (NEA, 2010). High amount of high-rise structures demonstrates the ongoing developments that is ongoing in the world’s densification. With the small diurnal temperature differences, it is a challenging environment for a test-case in cooling load reduction potential.

In Singapore, buildings, excluding those in the industry sector, consume more than half of the electricity generated. Previous research conducted by the Building and Construction Authority (BCA) of Singapore shows that office buildings’ energy
consumption accounts for 57% of the total electricity consumption in buildings. Absence of natural resources fundamental to the generation of electricity and with the increasing population and energy demand, energy is one of the critical factors for the development of Singapore’s economy, now and for the future. Energy consumption in offices has been rising in recent years because of the growth in information technology, air-conditioning, and intensity of usage. There is a great potential for energy savings as many of the buildings waste energy due to inefficient design and neglected operation.

Figure 1.4 Skyline Singapore City, 2014. Photo by Akanksha Dewan

Singapore is an urban city with no rural base, which depends heavily on air-conditioning to cool its buildings all year round. Though the actual percentage varies on climate, design and systems. Energy usage ranging from 100 up to 400 kWh/m2/year with a mean value of 282 kWh/m2 on a yearly base (Qi, 2006). Therefore, reduction of the reliance on these “mechanical” systems through natural ventilation systems should be investigated to make tall buildings more sustainable.

For an average office building the energy usage for heating ventilation air-conditioning and the needed fans to support the airflow is 117kWh per square meter a year (39%). In
Singapore the cooling demand is higher and with 164kWh (58%) it is above the average tall office building usage.

Office comfort requirements

This challenge is even bigger given Singapore’s office comfort requirements. Most of the 2,07 million employees are working in air-conditioned spaces that are cooled and de-humidified to achieve higher work productivity (Lee & Rajagopalan, 2008). The air-conditioning is becoming more a status symbol, it is a metaphor for the expertise Singapore has in many aspects of life, from labour and finance to its media and political debate. They create a western temperate office climate into a tropical climate. With a typical thermostat set-point at about 22 degrees. Companies that operate in prestigious markets often invest in two systems in case one breaks down. (Arnold, 2002).

Problem statement

Singapore’s climate is a TROPICAL CLIMATE with hot and humid conditions all year long. Under these weather conditions, cooling is crucial for the THERMAL COMFORT in TALL OFFICES BUILDINGS. COOLING LOAD REDUCTION is needed to enhance the reduction in the reliance on fossil fuels and development of the densification of urban areas.

1.2. Main Objectives

Promotion of energy system retrofit in existing tall office buildings in Singapore may bring benefits to building owners and tenants. To ensure that investments to retrofit buildings are put in the worthwhile projects, it is essential to predict energy saving accurately. As well as a beneficial value of a sustainable building, daylight experience should be implemented in the overall design.

Enhancing of passive cooling in tall office buildings in a tropical climate. Reducing energy usage by cutting out the use of continuous air conditioning usage. Challenging a natural ventilation strategy to realize a system that works during windy days, rainy days and sunny days without wind during working hours. The mediation of the façade in outdoor airflow and indoor thermal comfort. For this case the objective is the façade and the thermal comfort of its users and not the building itself as a part of a city.

The general objective:

“Testing a façade concept with PASSIVE VENTILATION STRATEGY for TALL OFFICE BUILDINGS in the TROPICAL CLIMATE of Singapore to achieve a COOLING LOAD REDUCTION without affecting the THERMAL COMFORT of the occupants.”
1.3. Research Questions

The general research question:

“How can we design a BUILDING SKIN to maintain a THERMAL COMFORTABLE office with WIND and STACK VENTILATION in a TALL OFFICE BUILDING in a TROPICAL CLIMATE to REDUCE THE COOLING LOAD?”

- What is the air INTAKE and OUTTAKE?
- What is the influence of SOLAR SHADING on the natural ventilation?
- What is the influence of a FLOORPLAN to the façade?
- What is the influence of PERSONAL COMFORT on façade design?

1.4. Sub questions

To create a certain framework, sub-questions need to be dealt with to engage the general research question.

- What are the different options for NATURAL VENTILATION PRINCIPLES for tall office buildings in a tropical climate using the building skin?
- What are the indoor temperature limits for a natural ventilated tall office building in a tropical climate based on the ADAPTIVE COMFORT MODEL?
- What WIND SPEEDS are acceptable in a tropical office building without having any DISCOMFORT?
- What are the WIND SPEEDS at 90 to 100m, and higher?
- What is the influence of HUMIDITY on thermal comfort?

1.5. Approach and methodology

The thesis exists of two products/parts. The design part, a more practical interpretation of the literature research with its own limitations and a theoretical part that is tested via a quantitative research method. In the end the overall conclusion will be based on the knowledge of both parts, making it a façade design with literature based arguments. The quantitative research into the topics thermal comfort and natural ventilation will provide parameters. These two parts deliver the design strategy and techniques when linked to the local climate and in combination with references. Together these four form the input for the design. Although design is still diverging at this moment with the help of calculations and computer models an optimization can be done, which will reduce the
amount of options. Of these options a single solution is chosen as general model to reply on the research questions and finally will lead to the drop or acceptance of the hypothesis:

“The use of local available natural resources, such as WIND AND STACK EFFECT, reduces the COOLING LOAD of TALL OFFICE BUILDINGS without affecting the THERMAL COMFORT of the occupants.”

The application of the research framework is done via thorough analysis of the thermal comfort, natural ventilation and the local climate. Reference projects are essential for the applicability of the literature and implementation of the local climate as only historical data is available.

To control the influence certain amount of control is necessary and therefore calculations are needed. Hand are needed to show the parameters; this is checked by computer simulations. This gives the general approach shown in the image on the right.
1.6. Scheme of thesis

The thesis is build up to initiate a guiding to the design process. Each chapter is linked to the next and will continue in converging towards the final design. In the research and design chapter the concept will be tested and the optimization tests the hypothesis, new insights may be done and thus small diversion.

Figure 1.8 Conversion in the thesis where the research and design is the chapter where knowledge and feedback give interaction on the process.
2. HIGH-RISE

Over the past one hundred and twenty years, the high-rise typology has developed a variety of paradigm shifts, influenced by regulatory changes, developments in technology and materials, changes in architectural thinking, economic and commercial drivers. This chapter describes the history and the current way we use high-buildings in the 21st century.
2.1. History

The skyscraper boom began in the capital of the American Midwest in 1885 with William Le Baron Jenney’s Home Insurance Building, which rose to its then-impressive height of 10 storeys (and, after an 1890 addition, 12) with metal construction, rather than just brickwork.

Chicago

Born out of a desire to maximise the financial return of a given plot of land, combined with developments in structural steel framing and the invention of the lift in the mid-nineteenth century, tall buildings quickly spread across North America, becoming the symbol of economic growth and prosperity. Energy was predominantly consumed in the heating of occupied spaces and providing vertical transport between floors.

Ventilation was naturally achieved through opening windows and artificial lighting levels were very low due to the inefficiencies of lighting technologies of the time with levels between 22 and 43 lux for office buildings in 1913 (current standards are 500 lux for offices) (Gabel et al., 2016). Quality and rentability of office space was depending on large windows and high ceilings that allowed daylight to penetrate as deeply as possible into the interior.
New York City

At the beginning of the 20th century, architects started to design many of the most prominent skyscrapers in New York. Iconic buildings such as the Chrysler Building (1930), and the empire state Building (1931) reached unprecedented heights while still relying on natural ventilation and lighting. The form of these skyscrapers and the depth of their plans were still driven by the need to provide natural light for office interiors with no particular emphasis to the development of a natural ventilation strategy.

The form and shape of the early high-rise buildings had an impact on the energy usage; typical high-rises constructed before the NEW YORK ZONING LAW OF 1916 were bulky and compact as result of repetitive stacking of large floor plates to maximise rentable floor area. These buildings were large volumes, but had relatively small amount of façade surface. To maintain natural light penetrating into the office spaces light courts were integrated into the buildings in E, H, and U-shaped with a maximum floor plan depth of 6.1 to 8.5 metres (Gabel et al., 2016).

By the 1950’s the availability of cheap energy and the affordable AIR-CONDITIONING had an impact on the form and planning of (office) buildings (Wood & Salib, 2013). The consideration of passive measures to provide comfortable indoor environments were no longer a central concern for architects and engineers allowing deep planned office buildings.

The heavy weight stone façade of the early 1950’s was replaced for transparent CURTAIN WALL SYSTEMS which made the introduction of the fully glazed box (Wood & Salib, 2013). Prominent architect Mies van der Rohe’s work in high-rise buildings is the example of the
all-glass-box architecture with his Seagram Building in New York (1958). The increased transparency and lightness of the structure, as well as the lack of solar shading devices makes the building comfort completely dependent air-conditioning system.

The oil crisis of 1973 was the initial changing point in the development of the skyscraper. Aiming to reduce energy consumption lead to insulating and completely sealing the façade. The idea of minimizing energy losses had a negative impact on the comfort and healthy of the occupants resulting in SICK BUILDING SYNDROME\(^1\) due to the bad air quality (Wood & Salib, 2013).

### Singapore

Singapore’s history of skyscrapers began with the 1939 completion of the 17-storey Cathay Building. The 70-metre structure was, at the time of its completion, the tallest building in Southeast Asia. Singapore went through a major building boom in the 1970s and 1980s that resulted from the city's fast industrialisation. In this time, the Overseas Union Bank Centre became the tallest building in the city; with its 280 meter it was as well the tallest building in the world outside of North America from its 1986 completion until 1989. The skyscraper-building boom continued during the 1990s and 2000s, with 30 skyscrapers with a minimum of 140 meter, many of them residential towers, constructed from 1990 through 2008 (Wiki, 2015).

Nowadays the skyline of Singapore contains multiple 200+ buildings. The tallest seven are shown in the table 2.2. There is no direct relation between orientation and floorplan visible. The facades don’t show any exterior shading, only Raffles place has some deep laying windows. Whereas the ideology of the bioclimatic skyscraper should include the local climate into designs. Making the buildings rely on electrical systems to control the indoor climate.

The air-conditioner is in the environment of Singapore a metaphor for the prosperity of Singapore and is becoming less about cooling people. Companies that operate in international markets often invest in two systems in case one breaks down. They create

\(^1\) Sick building syndrome: The term "sick building syndrome" (SBS) is used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. The complaints may be localized in a particular room or zone, or may be widespread throughout the building (EPA, 2010).
a temperate *western office climate* in a tropical climate. With a typical thermostat set point around 22 degrees Celsius (Arnold, 2002).

Table 2.1 Overview of the seven tallest offices in Singapore. Includes tips and architectural details but does not include antenna masts (Emporis, 2016; Wiki, 2015).

<table>
<thead>
<tr>
<th>Facade</th>
<th>Height [m]</th>
<th>No. Floors</th>
<th>Floor plan</th>
<th>F to F [m]</th>
<th>F to C [m]</th>
<th>Plenum + floor [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Raffles place</td>
<td>280</td>
<td>63</td>
<td><img src="image1.png" alt="Floor Plan" /></td>
<td>4.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Republic plaza</td>
<td>280</td>
<td>66</td>
<td><img src="image2.png" alt="Floor Plan" /></td>
<td>4.0</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>United Overseas Bank Plaza One</td>
<td>280</td>
<td>67</td>
<td><img src="image3.png" alt="Floor Plan" /></td>
<td>-</td>
<td>2.7</td>
<td>-</td>
</tr>
<tr>
<td>Capital tower</td>
<td>254</td>
<td>52</td>
<td><img src="image4.png" alt="Floor Plan" /></td>
<td>4.2</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>One Raffles Quay North Tower</td>
<td>245</td>
<td>50</td>
<td><img src="image5.png" alt="Floor Plan" /></td>
<td>-</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>Marina Bay Financial Centre Tower 3</td>
<td>245</td>
<td>50</td>
<td><img src="image6.png" alt="Floor Plan" /></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ocean Financial Centre</td>
<td>245</td>
<td>43</td>
<td><img src="image7.png" alt="Floor Plan" /></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2. Space efficiency

The relationship between cost and benefit is a complex question in today’s global marketplace. Political ideology plays an important role in the globalization process. Tenants appreciate the landmark status and politicians are pleased with the symbolic role of high-rise buildings. Nonetheless high-rise office buildings are more expensive to
construct per square meter, they produce less usable space and their operation costs are more expensive than conventional office buildings. The space efficiency, as well as the shape and geometry of the high-rise building need to satisfy the value and cost of the development equation.

**Structural efficiency and floor slab size**

Space efficiency, which is determined by the size of the floor slab, dimension of the structural elements and rationalized core, goes along with the financial benefit. Maximum space efficiency is found by the maximum ratio in floor slab shape and total floor area (Ayşin & Özgen, 2009). Height of the office building affects the floor slab efficiency, as the core and structural elements increase relatively to the overall floor slab to support vertical circulation and load bearing functions. Consequently tall slender office buildings are more expensive to build as they have a lower space efficiency due to the high amount of structural surface space.

*Table 2.2 Tall office buildings in the world. Height, floor to floor height (F to F) & floor to ceiling height (F to C), space efficiency (Ayşin & Özgen, 2009).*

<table>
<thead>
<tr>
<th>Name of Building</th>
<th>floors</th>
<th>Height [m]</th>
<th>F to F [m]</th>
<th>F to C [m]</th>
<th>plenum + floor [m]</th>
<th>space efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taipei 101 T.</td>
<td>101</td>
<td>509</td>
<td>4.2</td>
<td>2.8</td>
<td>1.4</td>
<td>72</td>
</tr>
<tr>
<td>Shanghai WFC</td>
<td>101</td>
<td>492</td>
<td>4.2</td>
<td>2.8</td>
<td>1.5</td>
<td>70</td>
</tr>
<tr>
<td>Petronas T. 1-2</td>
<td>88</td>
<td>452</td>
<td>4.0</td>
<td>2.7</td>
<td>1.4</td>
<td>60</td>
</tr>
<tr>
<td>Sears Tower</td>
<td>114</td>
<td>442</td>
<td>3.9</td>
<td>2.7</td>
<td>1.2</td>
<td>77</td>
</tr>
<tr>
<td>Jin Mao Tower</td>
<td>88</td>
<td>421</td>
<td>4.0</td>
<td>2.8</td>
<td>1.2</td>
<td>69</td>
</tr>
<tr>
<td>Two International Finance Center</td>
<td>88</td>
<td>415</td>
<td>4.0</td>
<td>2.7</td>
<td>1.3</td>
<td>68</td>
</tr>
<tr>
<td>CITIC Plaza</td>
<td>80</td>
<td>391</td>
<td>3.9</td>
<td>2.7</td>
<td>1.2</td>
<td>67</td>
</tr>
<tr>
<td>Shun Hing Square</td>
<td>69</td>
<td>384</td>
<td>3.8</td>
<td>2.7</td>
<td>1.1</td>
<td>67</td>
</tr>
<tr>
<td>Central Plaza</td>
<td>78</td>
<td>374</td>
<td>3.9</td>
<td>2.6</td>
<td>1.3</td>
<td>66</td>
</tr>
<tr>
<td>Bank of China</td>
<td>70</td>
<td>367</td>
<td>4.0</td>
<td>2.8</td>
<td>1.2</td>
<td>69</td>
</tr>
<tr>
<td>average</td>
<td>88</td>
<td>425</td>
<td>4.0</td>
<td>2.7</td>
<td>1.3</td>
<td>69</td>
</tr>
</tbody>
</table>

According to Yeang, floor slab efficiency of a typical high-rise office building should generally not be less than 75%, unless the site is too small or too irregular to permit a higher level of space efficiency. Floor slab designs using clever devices, such as scissor stairs, pressurized lift shafts, dispersal of toilets etc. can increase efficiency up to 80% - 85% per typical floor (Ayşin & Özgen, 2009).
Floor to floor height

Office buildings require a variety of floor-to-ceiling heights ranging between 2.6 and 2.8m. Depth of the structural floor system varies depending on the floor loads, size of structural bay, and type of floor framing system. In the case of steel floor framing, an allowance for fire-proofing must be made. However, in steel systems, increasing the structural depth will result in decreased weights of profiles. Trusses, which permit the passage of ducts, provide structural depth without increase in floor-to-floor height.

Values for floor to floor and floor to ceiling are found to be coherent for global buildings and in Singapore. The analysis shows the lower limit to be in line with the European guidelines for minimum floor to ceiling height in offices (2.6 meter)(EC, 2011 ). Differences in plenum and floor thickness are due to different structural systems and ducting, ranging from 1.1 to 1.5 meter in buildings spread around the world. For the two cases this value is found in Singapore respectively 1.4 and 1.5 meter, showing a deviation from the average of 1.3 meter found in the analysis of tall buildings of Ayşin & ÖZGEN (Ayşin & ÖZGEN, 2009).

2.3. Ventilation modes

As a response to the oil crisis and the development of the sick building syndrome architects and engineers had to provide other solutions for energy conservation measures could provide a healthier and more comfortable environment. The start of greater building energy efficiency and a return to considering the benefits of natural ventilation in buildings, as well as passive heating and cooling strategies in office building designs (Wood & Salib, 2013).

Passive mode

Passive mode is designing for thermal comfort without the use of any active electromechanical systems. The design strategy for the form must start with bioclimatic design (appropriate building configurations and orientation in relation to the local climate and appropriate façade design). This can significantly influence the configuration of the built form and its enclosure form.

Bioclimatic design approach

In the bioclimatic design approach, low-energy objectives are achieved through passive means (such as through shaping the built-configuration, placement of the building components, and selection of materials), rather than through the use of electromechanical devices and systems. These electro mechanical devices and systems might
subsequently be added to the building’s management and facade systems to further enhance its low energy performance. These should be regarded as secondary to design by low-energy passive means.

The design of bioclimatic skyscrapers demands a variable approach for facade design and building performance. The location’s sun paths are different for each facade at different times of the day, year and geographical location. The objective in the climate responsive approach is to seek year round comfort with entirely passive energy means where possible to reduce energy consumption. The outcome of the bioclimatic design should be a ‘high quality’ building and its approach is applicable to all climate zones (Yeang, 1997).

Menara Umno in Penang, Malaysia

The Menara UMNO is located on the island of Penang, with twenty-one storeys. The form is derived from the conflict between the geometry of the site and the local climate. Using slim rectilinear plan forms on the dense urban site. The building is unique for being naturally ventilated. The use of ‘wing-walls’, vertical walls with the full height of the building channel the prevailing wind into the building and create high- and low-pressure areas (Yeang & Powell, 2007).

Figure 2.7 Passive mode building of Ken Yeang. Menara Umno, Penang, Maylasia, 1998.

Mixed-Mode

Solely relying on natural ventilation is limited by the local site, climate conditions and comfort demands. Normally architects choose for an easy way out without any responsibility and rely on a HVAC system. This is an understandable, since it reduces the
risks associated with a purely natural system. However it means that the full benefits such as reduced capital and running costs and carbon reduction of a natural system will not be achieved (Etheridge & Ford, 2008).

In this case, mixed-mode or hybrid ventilation presents a suitable strategy that uses a combination of natural ventilation (from vents or windows) and mechanical systems which offer some form of cooling and air distribution (Wood & Salib, 2013). Mixed mode buildings are generally classified on the basis of their operation strategies. Such mixed mode ventilation strategies are typically classified into the following:

I. Contingency

The building is designed either as an air-conditioned building with provision to switch to natural or as a naturally ventilated building with space and electrical infrastructure allocated for the possible installation of mechanical equipment for air-conditioning in the future (Wood & Salib, 2013).

II. Zoned

In a building where mechanical cooling and natural ventilation operate in different areas or zones of the building. This can be a solution for conditioned meeting rooms, or any other high dense space and natural ventilated work spaces (Wood & Salib, 2013).

III. Complementary

For a complementary strategy the building is designed in a way that there is the ability to operate under mechanical and natural ventilation mode in the same space. This category is further dived by alternate, changeover and concurrent mixed-mode strategies (Wood & Salib, 2013).

- **Alternate**: where the building includes provisions and equipment for both air conditioning and natural ventilation, but operates continuously in one mode or the other.
- **Changeover**: where the building switches between mechanical cooling and natural ventilation on a seasonal or daily basis, depending on the outside weather conditions.
- **Concurrent**: where mechanical cooling and natural ventilation can operate in the same space at the same time. This strategy is to extend the comfort zone of the occupant to natural ventilation level, and delivers cooling necessary cooling with the HVAC system. By supplementing the HVAC system energy can be saved.
Mixed mode buildings often use sophisticated building management systems and control strategies which allow for the overlap between the natural ventilation system and the mechanical system. In Germany there are several buildings which incorporate the mixed-mode strategy successful.

**Table 2.3 Characteristics of typical naturally ventilated, air conditioned, and mixed-mode buildings (Brager, Ring, & Powell, 2000).**

<table>
<thead>
<tr>
<th>Naturally Ventilated (NV)</th>
<th>Air Conditioned (AC)</th>
<th>Mixed-Mode (MM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building Form</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small floorplates, which allow cross-ventilation and generous ceiling heights are typical.</td>
<td>Large floorplates with relatively low ceiling heights are often preferred.</td>
<td>A plan depth of no more than 15 m is recommended to take full advantage of natural ventilation.</td>
</tr>
<tr>
<td><strong>Windows &amp; Lighting System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows are relatively small and are operable. Daylighting is preferred to avoid internal heat gains associated with artificial lighting.</td>
<td>Glazing is sealed and often deeply tinted to limit solar heat gain. High glass-to-wall ratios are typical. Fluorescent lighting is standard.</td>
<td>Windows are operable and may include both automatic and occupant control. Window design and controls are more complex than NV or AC.</td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control of indoor conditions is dependent on occupant behavior. Occupants must both respond to and predict outdoor conditions in determining how much to ventilate the building.</td>
<td>HVAC controls may be complex and are generally handled by automated systems, using feedback control. System operators play a key role in maintaining the system.</td>
<td>Control may be a combination of occupant and automatic control systems. Both feedback (responsive) and feed-forward (predictive) strategies should be employed.</td>
</tr>
<tr>
<td><strong>Occupant Comfort</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupant comfort is largely dependent on external conditions, which may vary significantly seasonally and daily.</td>
<td>HVAC system strives to maintain uniform thermal conditions. Occupant comfort is closely linked to HVAC system performance.</td>
<td>Occupants have control with a/c system providing “background” cooling and ventilation. AC provides relief if NV system fails (or vice-versa).</td>
</tr>
<tr>
<td><strong>Ventilation Rate &amp; IAQ</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation rates are very high during temperate and warm outdoor conditions. IAQ is rarely a problem.</td>
<td>Ventilation rate is often fixed in a minimal position. HVAC system may cause IAQ problems if not maintained properly.</td>
<td>On average, ventilation rate will be somewhat higher than AC bldgs. NV can provide quick relief if IAQ problems emerge.</td>
</tr>
<tr>
<td><strong>HVAC Energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relatively little HVAC energy is consumed.</td>
<td>HVAC energy use varies depending on system design and operation. Often systems operate inefficiently for extended periods with little or no correction.</td>
<td>HVAC energy use should be less than AC buildings. Energy may be wasted, however, if NV and AC systems are not carefully coordinated.</td>
</tr>
</tbody>
</table>
2.4. Conclusion on high-rise

History shows us that technical improvements have given more freedom for floor plan design. With air-conditioning every building can be comfortable and with low energy cost energy is wasted. Within the highest buildings there are no external shading devices or operable windows to minimize cooling loads.

Floor slab efficiency is a reflection of the form of the building; a slender tall office building will require more supportive functions and thus leaves less rentable floor. A decent high-rise structure shouldn’t score lower than 75% efficiency. Floor to floor height for high-rises buildings around the world is around 4 meters (3.9 – 4.2m), this is in line with the analysed tall office buildings in Singapore (4.0 – 4.2m). Overall floor to ceiling height is in range from 2.6 – 2.8 meters. Variation in floor thickness and structural system causes fluctuations in plenum height (plenum + floor, 1.1 – 1.4m).

German references show an innovative design which can improve the work environment and productivity with solely passive and mixed modes. To further increase energy efficiency passive design should be part of the de the first level of design consideration in the process. Followed by other modes that can further enhance energy efficiency.

To break with current tradition reduction in energy should start in the optimal use of environmental resources in building design. In passive building design the use of wind wings, double facades have proved that it is possible to reach thermal comfortable environment.

Bioclimatic design requires an understanding of the local climatic conditions, not just a synchronization with the meteorological conditions. Furthermore, if the design optimizes its passive modes, it remains at an improved level of comfort during any electrical power failure. Without a passive design strategy in case of power failure the building may become intolerable to occupants.

The use of mixed mode strategy provides a comfortable environment with the use of natural resources where possible and is based on a passive mode design to improve thermal comfort. The next chapter will analyse the local climate in order to optimal implement the bioclimatic façade design for Singapore.
This chapter is the introduction to the literature study. Singapore is a modern city where comfort is obligatory in the indoor environment. Possible cooling strategies to minimize the energy usage for HVAC systems in the tropical climate will be discussed as well as a general overview of the climatological data.
3.1. Climate zones.

Metrological differences are due to geographical differences, location, altitude, availability nearby water etc. We can define several amount of climate zones in the world. The climate classification based on the work of Wladimir Köppen (dates from 1900), continues to be the most widely used climate classification over a century later (Peel, Finlayson, & Mcmahon, 2007). The continental and island maps are combined together to form the World Köppen-Geiger Climate Type map (Figure 3.1.). The dominant climate class by land area is arid (B, 30.2%) followed by cold (D, 24.6%), tropical (A, 19.0%), temperate (C, 13.4%) and polar (E, 12.8%). The most common individual climate type by land area is BWh (14.2%), followed by the Aw (11.5%).

![Figure 3.1. World map of Köppen-Geiger climate classification (Peel et al., 2007)](image)

The five main climates consist together of 30 different sub climates. Each defined by its characteristics (more about this in the appendix). Four of the main climates by Köppen are general used for the design of buildings; Tropical, Arid, Temperate and Cold climate.

**Table 3.1. Overview characteristics of the 4 building design climates by Köppen-Geiger.** (Peel et al., 2007) $P_{\text{threshold}}$ refers to a local value explained in the appendix.

<table>
<thead>
<tr>
<th>Tropical</th>
<th>Arid</th>
<th>Temperate</th>
<th>Cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{cold}} \geq 18^\circ\text{C}$</td>
<td>$\frac{\text{Mean annual precipitati}}{\leq P_{\text{threshold}}}$</td>
<td>$T_{\text{hot}} &gt; 10^\circ\text{C}$ &amp; $T_{\text{cold}} = 0 - 18^\circ\text{C}$</td>
<td>$T_{\text{hot}} &gt; 10^\circ\text{C}$ &amp; $T_{\text{cold}} \leq 0^\circ\text{C}$</td>
</tr>
</tbody>
</table>
Sub-tropical vs Tropical climate

Nicol specifies four climates for the purpose of building design (Cold, Temperate, Hot & Dry and Warm & Humid) without mentioning the tropical climate (Haase and Amato 2009). The problem arises what is the difference between tropical and warm and humid. According to Haase the warm-humid climate is defined by high humidity something Köppen doesn’t refer to in his characteristics of a tropical climate (Table 3.1.). He uses the amount of precipitation to separate the Rainforest, Monsoon and Savannah climate, but not the relative humidity (Peel et al., 2007).

We can generalize the location of the tropical climate with its location. The tropical climate is located between 23.5° North and 23.5° South (figure 3.2.) beginning from the equator (Jai Kanth, 2005). This is similar to the updated climate classification map of Köppen-Geiger (figure 3.3.). Getting closer to the Equator the colour gets more dark blue on the Köppen-Geiger map (figure 3.3.) (Af climate = Rainforest).

The subtropics are geographic and climate zones located roughly between the tropic circle of latitude (the Tropic of Cancer and Tropic of Capricorn) and the 38° North and South parallel in each hemisphere. Due to altitude differences the subtropical climate can exist at high elevations within the tropical zones.

Possible climate change

According to the intergovernmental panel on climate change (IPCC), global temperatures are projected to rise by 1.1 °C – 6.4 °C by 2100 over 1990 levels, while global mean sea levels are expected to increase by 18-59 cm over the same period based on future scenarios of varying global emissions levels. Temperature extremes, heat waves and heavy rainfall events are projected to become more frequent as well. For Southeast Asia warmings are also projected to increase about 7%. Based on the projections of 21 models, the predicted annual rainfall changes for Southeast Asia range from -2% to +15% with a median change of +7% (NEA, 2010).
Table 3.2 Summarized findings show consistent with the projections in the IPCC assessment report (AR4) (NEA, 2010)

<table>
<thead>
<tr>
<th>Climate Change Projections (in 2100 relative to present)</th>
<th>IPCC AR4 Projections</th>
<th>Phase 1 Study Local Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Average Temperature [°C]</td>
<td>+1.7 to +4.4 (A1B Scenario, SE Asia)</td>
<td>+2.7 to +4.2</td>
</tr>
<tr>
<td>Change in Rainfall [%]</td>
<td>-2% to +15% (A1B Scenario, SE Asia)</td>
<td>No discernible trend. Further studies needed.</td>
</tr>
<tr>
<td>Change in Mean Sea Level [m]</td>
<td>+0.18 to +0.59 (All IPCC Scenarios, Global)</td>
<td>+0.24 to +0.65 (3 IPCC Scenarios)</td>
</tr>
</tbody>
</table>

3.2. Passive and active cooling strategies

Improving energy efficiency of a building depends on its heat or cooling load and possibilities of harvesting sustainable energy (solar, wind etc.). For the four different types of climates we can specify the following problems:

- Cold climates, where the main problem is the lack of heat,
- Temperate climates, where there is a seasonal variation between under heating and overheating,
- Sub-tropical climates, where the main problem is overheating but the air is dry with a large diurnal temperature variation.
- Tropical climates, where overheating is not as great as in sub-tropical areas but it is intensified by small diurnal temperature variation.

A clearer overview of the problems can be seen in relation with the climatic data of specific cities. In the table below (table 3.3) four different cities in four different climates are analysed and given the general climate specifications of temperature and humidity. Where relative humidity is in general depending on the temperature which is in lower during the day (warmer temperature due to the sun) and lower during the night. In the table there is only a big difference in humidity between the sub-tropical climate and the others.

Table 3.3 Overview general climate characteristics of 4 cities. Sources:* (Wood & Salib, 2013, pp. 142, 143) **weatherspark.com ***climate consultant

<table>
<thead>
<tr>
<th>Climate type</th>
<th>Cold</th>
<th>Temperate</th>
<th>Sub-tropical</th>
<th>Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Winnipeg, Canada*</td>
<td>London, UK*</td>
<td>Santiago de Chile**</td>
<td>Singapore***</td>
</tr>
<tr>
<td>Mean annual temperature</td>
<td>3°C</td>
<td>11°C</td>
<td>21°C</td>
<td>28°C</td>
</tr>
<tr>
<td>Average daytime Temperature hottest</td>
<td>25°C</td>
<td>22°C</td>
<td>29°C</td>
<td>33°C</td>
</tr>
</tbody>
</table>
Passive cooling techniques

Four basic strategies as alternative for HVAC systems can be identified on building scale: adiabatic, geothermal, dehumidifying and natural ventilation. To overcome overheating extra techniques as night time ventilation and shading can be implemented as well as further energy savings can be done by daylight control.

Table 3.1 Overview cooling techniques

<table>
<thead>
<tr>
<th>Cooling technique</th>
<th>Environmental requirements</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic</td>
<td>Low humidity level</td>
<td>Evaporative cooling</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Day night, or seasonal temperature difference.</td>
<td>Heat sink in summer, heat buffer in winter.</td>
</tr>
<tr>
<td></td>
<td>Temperature of groundwater</td>
<td></td>
</tr>
<tr>
<td>Dehumidification; Refrigerate</td>
<td>Cold water</td>
<td>remove moisture from air</td>
</tr>
<tr>
<td>Dehumidification; Desiccant</td>
<td>Heat is required to regenerate the desiccant</td>
<td>A desiccant wheel is used to remove moisture from the air</td>
</tr>
<tr>
<td></td>
<td>Only effective during daytime, airflow is required via operable windows</td>
<td>Airflow can increase comfort temperature &amp; remove excessive heat</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>lower external air temperatures at night</td>
<td>reduces peak daytime temperatures by cooling thermal mass</td>
</tr>
<tr>
<td>Night time ventilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase change materials</td>
<td>Temperature differences, ≥ 10°C</td>
<td>store and release heat to reduce the cooling load</td>
</tr>
<tr>
<td>Thermal mass</td>
<td>Temperature differences, ≥ 10°C</td>
<td>store and release heat to reduce the cooling load</td>
</tr>
<tr>
<td>Solar shading</td>
<td>-</td>
<td>shading can prevent the building form overheating</td>
</tr>
<tr>
<td>Daylight</td>
<td>-</td>
<td>If applied well, internal heat load can be reduced</td>
</tr>
</tbody>
</table>

Adiabatic

Adiabatic cooling or evaporative cooling is the adding of water or moisture to the air lowering the temperature of the air. Air temperature and humidity are the two major parameters affecting thermal comfort significantly, and only sensible load can be handled by an evaporative cooling system. A conventional evaporative cooling system is suitable for dry and temperate climate where the humidity is low (Riangvilaikul & Kumar,
2010). In hot and humid climates, the ambient air temperature ranges from 20 to over 30 °C, while the relative humidity varies from 40 to 95%.

**Geothermal**

Geothermal energy is stored in the ground. In combination with a heat pump heat can be stored seasonally and even daily. Temperature surveys of groundwater have taken on new significance as the several forms of geothermal energy become more important. Principally, shallow groundwater has great potential as a heat source or sink for domestic heating and cooling. Groundwater, heat pumps have already begun to assume a significant share of the domestic environment control load in many areas and will therefore have an increased impact on groundwater systems (NGWA, 1999). In this case the ground acts as a heat buffer in winter and as heat sink in summer. The differences in day night temperature and seasonal differences contains the potential to store energy which can be used later.

**Dehumidification**

With dehumidification the humidity in the air is lowered to improve the evaporative function of the human skin. This can be done with a refrigerator technique; with a cold surface increasing the amount of moisture till the level it condenses. Or with desiccant that absorb humidity and relieve it later.

**Refrigerate**

A good example of refrigerate dehumidification application in building engineering is the Manitoba Hydro Place. The building makes use of 24 meter high waterfalls which depending on the season add moisture to the air in summer and absorb humidity in winter. This is possible if the water supply has a different temperature than the air temperature. In Winnipeg Canada the cold climate can make use of the seasonal differences to store water in the ground. In this case cold water in summer is used and vice versa in winter (Wood & Salib, 2013).

**Desiccant**

Solid or liquid desiccants can be used to remove moisture from air, with the desiccant subsequently regenerated using solar thermal heat such as can be provided by flat-plate solar thermal collectors. Heat is required to regenerate the desiccant. A great advantage of desiccant cooling systems is that they avoid overcooling the air and then reheating it for dehumidification purposes.

However, the COP (coefficient of performance) of a desiccant system is typically only about 1.0, compared to typical values of four to six for electric chillers, so primary energy use may increase or decrease, depending on the efficiency of the electric power plant.
that supplies the displaced electricity and the extent of overcooling. However, in the hot and humid climate of Hong Kong, solid desiccant systems can reduce overall energy use for cooling and dehumidification by 50% if solar thermal energy is used for regeneration of the desiccant (Ürge-Vorsatz, 2012).

Night time ventilation

Night-time ventilation is a strategy used to cool down the building structure via lower external air temperatures at night, providing the building has a high thermal mass and exposed structure. This strategy employs the building’s thermal mass as an intermediate storage medium, allowing the structure to absorb the heat built up during the day and to flush it away during the night. In the appropriate climate this is a suitable solution for office buildings which are typically occupied during the daytime only. As the coolness is stored in the thermal mass. It reduces peak daytime temperatures and improving internal comfort conditions during work hours. It moderates temperature fluctuations inside the building (Wood & Salib, 2013, p. 21).

Heat absorbers (mass)

Thermal mass

Thermal mass refers to the heat capacity of materials. Absorbing, storage and the release of it later. Building components such as walls, partitions, ceilings, floors and furniture of a building that can store thermal energy are used. It helps in the regulation of indoor temperature by absorbing and releasing the heat gained through both external and internal means. This has a delaying/reducing effect on the peak indoor loads and decreasing the mean radiant temperature.

For thermal storage to be effective, the diurnal ambient temperature variation should exceed 10 K (Sadineni, Madala, & Boehm, 2011). The thermal mass optimization is affected by the properties of the building material, building orientation, thermal insulation, ventilation, other cooling systems and occupancy patterns. This passive building energy efficiency technique is more effective to buildings such as offices that are unoccupied during the night when the thermal mass can be cooled with night time ventilation (Sadineni et al., 2011).

Phase change materials

Phase change materials (PCM) store and release heat to reduce the cooling and heating loads of a building. They basically function as a thermal mass and accomplish that by liquefying as they absorb heat, preventing the heat from reaching the conditioned space and releasing the heat when the outside temperature decreases (typically at night). With organic-based PCM (BioPCM) energy savings of about 30% and a shift in maximum peak load of about 60 min (Sadineni et al., 2011).
Natural ventilation

Natural ventilation allows the inhabitant access to air flow that can be used to cool and ventilate the space. The airflow is naturally driven due to wind and buoyancy effect. Depending the climate and the available natural resources to be sufficient. This passive use of air currents over mechanical means of air-conditioning reduces the energy consumption of the building. In turn reduces the CO\textsuperscript{2} output of the building in the operational phase of the building (Boake, 2001).

Operable windows are used to enhance natural ventilation. High velocity winds and prevailing direction at the higher altitudes of high-rise buildings should increase its potential. Natural ventilation of offices by fresh air is much more acceptable to the building’s users and it has the additional benefits of reducing investment in air handling systems and also reducing energy consumption (Boake, 2001).

Daylight savings

The economic benefit of daylighting is enhanced by the fact that it reduces electricity demand most strongly when the sun is strongest, which is when the daily peak in electricity demand tends to occur during summer. Daylighting can also reduce cooling loads. This is because the luminous efficacy (the ratio of light to heat) of natural light is 25–100\% greater than that of electric light systems (Ürge-Vorsatz, 2012).

Sun-shading

Shading of openings may be required or privacy considerations can be a driver to block direct visual contact between inside and outside. For cooling purposes sun shading is an effective cooling method, especially in the full glass box architecture shading can prevent the building form overheating. The most common form of shade is an exterior fixed horizontal overhang. These are used on the side of the building facing the sun’s path, sometimes including east and west faces. However, east and west faces often have more need of vertical fins to avoid low-angled sun.

The side of the building facing away from the equator needs no shading, except near the equator where the sun may be on the north or south side depending on the season (O’Connor, Lee, Rubinstein, & Selkowitz, 1997). There are many variations on fixed external shades, to reduce the profile and/or let more diffuse light in (figure 3.6).
3.3. Characteristics of the local climate in Singapore

Singapore is a country in South East Asia. The country is an island with neighbouring country Indonesia. It is an island and has Singapore City as its capital. The population of Singapore in 2005 was estimated by the United Nations (UN) at 4,296,000. With a density of 6,929 per square kilometre Singapore is virtually a city-state, and the entire population (100%) is considered urban (Nations, 2007).

Location

Singapore city, situated at latitude 1°21’ north and longitude 103°49’ east, experiences a climate with high temperatures, high humidity and abundant rainfall throughout the year. It has a diurnal temperature range of minimum 23–27°C and maximum 30–34°C. The mean monthly temperature does not vary by more than 1.2°C from the mean annual
temperature of 27.5°C and the average variation is 7°C with a mean annual relative humidity of 84%.

Singapore’s geographical location and maritime exposure places its climate at a limited seasonality scale, under the control of a monsoon circulation pattern. The Northeast monsoon prevails during December to March and the Southwest monsoon from May to September, both are characterized by rainy periods with persistent trade winds, and separated by two relatively short inter-monsoon periods with light and variable winds. Wind directions are from the North and Northeast directions during the Northeast monsoon while those in the Southwest monsoon are from the south and southwest.

Variability of wind velocities occurs between day and night. Night time velocities from 11pm to 7am are generally below 1.0 m/s. However, as surface heating progresses during daylight hours, thermally drivel local circulation can give rise to higher wind speeds.

**Metrological data**

Metrological data is derived from the airport, it is located ten meters above ground level and approximately 20 kilometres from the city centre of Singapore (figure 3.5). Therefore this data has to be used with care.

**Temperature**

![Graph showing average dry bulb temperature per month](image)

*Figure 3.8 Average dry bulb temperature per month. Data from climate consultant*

Compared to countries in the temperate regions, temperatures in Singapore vary little from month to month and also from day to day. The daily temperature range has a minimum of 23 to 25 during the night and maximum of 31 to 33 during the day. May and June has the highest average monthly temperature (24-hour mean of 28.2 and 28.5 respectively) and December is the coolest (26.3). Singapore, also has a coastal climate. The proximity of the sea has a moderating influence on its climate. This is because water has a larger heat capacity than the land surface, and a greater amount of heat is required to increase the sea temperatures. During afternoons, conditions at the coast are often
relieved by sea breezes. The presence of significant wind speeds, rainfall and cloud cover are the most important natural influences in mitigating the tropical heat.

The temperature of the groundwater is generally equal to the mean air temperature above the land surface. It usually stays within a narrow range year-round. (NGWA, 1999) Meaning that the groundwater is will be around 26 to 28 degrees.

Relative Humidity

Relative humidity shows a uniform pattern throughout the year and does not vary much from month to month. Daily variation is more marked, varying from more than 90% in the morning just before sunrise and falling to around 60% in the mid-afternoon on days when there is no rain. The mean annual relative humidity is 83.6%. Relative humidity frequently reaches 100% during prolonged periods of rain.

Sunshine and radiation

Sunshine duration refers to the cumulative time during which an area receives direct irradiance from the sun of at least 120 Watts/m². Since Singapore is near the equator, the length of the days are relatively constant throughout the year, and thus so is the amount of sunshine it receives. Daily sunshine hours are mainly influenced by the presence or absence of cloud cover.

In the sun path diagram we can see the altitude of the sun during the year. During work hours the sun has the largest in pack on the west side. Reaching up to 500 kWh on yearly base.

Although the hottest moment of the day the sun is right above the building. Where in the last months and the first
months of the year the sun is on the Southside. In the middle of the year the sun is on the north facade. With the morning sun on the East and the afternoon on the Westside all the sides will see a similar amount of sun.

Wind

The most prominent winds in Singapore are from the northeast and the south, reflecting the monsoon seasons in Singapore. On any given day, winds generally follow the prevailing monsoon flow except when light winds are being modified by terrain or weather systems (e.g., showers or thunderstorms and land or sea breezes). Wind directions are mainly from north to northeast during the Northeast Monsoon (December to March) and from the south to southeast during the Southwest Monsoon (June to September). Wind strength is greater during the Northeast Monsoon. The inter-monsoon months (April, May, October and November) are transition periods between the monsoons and show lighter and more variable winds.

Nebulosity

Although Singapore lies in the tropics, the skies are often grey. There is no significant difference in clouds during the day and night. With the high relative humidity level and low hanging clouds the feeling temperature is often higher than the operative temperature is. The amount of daylight is scattered by the clouds.
Precipitation

Rainfall is plentiful in Singapore and it rains an average of 178 days of the year. Much of the rain is heavy and accompanied by thunder. The long-term mean annual rainfall total is 2331.2mm (based on long-term records from 1869 to 2015).

There is no distinct wet or dry season in Singapore, monthly variations in rainfall do exists. Higher rainfall occurs from November to January during the wet phase of Northeast Monsoon season, when the major tropical rain-belt is positioned close to Singapore. The driest month is February which is during the dry phase of the Northeast Monsoon when the rain-belt has moved further south to affect Java.

Rainfall in Singapore shows a marked diurnal variation, with rainfall occurring more frequently during the daytime, particularly in the afternoons when solar heating is strongest. In terms of spatial distribution, rainfall is higher over the northern and western parts of Singapore and decreases towards the eastern part of the island.

Overview metrological data

The table below shows the values for each month and the yearly average. Work hours are 9:00 - 18:00, nights are from 23:00 – 7:00 and day average is for the full 24H.

Figure 3.15 Figure 3.8 Hourly variation of rainfall for each month (1982-2015). (MSS, 2015)

Figure 3.16 Annual average rainfall distribution (1982-2015). (MSS, 2015)

Figure 3.17 Rain occurs during the whole year, it rains on average 178 days a year and is more likely to rain during the day. (Photo: http://www.fivestarsandamoon.com/)
#### Table 3.3 Climate data for Singapore from Climate Consultant *data from (MSS, 2015)

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry bulb °C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work average</td>
<td>28.4</td>
<td>29.2</td>
<td>29.7</td>
<td>30.1</td>
<td>29.6</td>
<td>29.8</td>
<td>29.2</td>
<td>29.2</td>
<td>29.2</td>
<td>28.7</td>
<td>29.2</td>
<td>28.3</td>
<td>27.9</td>
</tr>
<tr>
<td>Min</td>
<td>22.8</td>
<td>22.4</td>
<td>24.0</td>
<td>22.7</td>
<td>24.0</td>
<td>23.0</td>
<td>22.0</td>
<td>22.9</td>
<td>21.0</td>
<td>23.2</td>
<td>23.0</td>
<td>23.0</td>
<td>22.8</td>
</tr>
<tr>
<td>Max</td>
<td>32.2</td>
<td>33.0</td>
<td>33.0</td>
<td>33.8</td>
<td>33.0</td>
<td>33.0</td>
<td>32.3</td>
<td>33.0</td>
<td>32.5</td>
<td>32.9</td>
<td>33.0</td>
<td>31.1</td>
<td>32.8</td>
</tr>
<tr>
<td>Night average</td>
<td>25.1</td>
<td>25.4</td>
<td>25.8</td>
<td>26.4</td>
<td>26.8</td>
<td>27.1</td>
<td>26.2</td>
<td>26.2</td>
<td>25.7</td>
<td>26.0</td>
<td>25.2</td>
<td>24.8</td>
<td>25.9</td>
</tr>
<tr>
<td>Day average</td>
<td>26.7</td>
<td>27.2</td>
<td>27.6</td>
<td>28.1</td>
<td>28.2</td>
<td>28.5</td>
<td>27.8</td>
<td>27.8</td>
<td>27.2</td>
<td>27.5</td>
<td>26.7</td>
<td>26.3</td>
<td>27.5</td>
</tr>
<tr>
<td><strong>Humidity %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work average</td>
<td>75.0</td>
<td>73.7</td>
<td>74.8</td>
<td>73.2</td>
<td>76.3</td>
<td>74.9</td>
<td>75.9</td>
<td>74.7</td>
<td>76.1</td>
<td>76.0</td>
<td>81.4</td>
<td>79.2</td>
<td>76.0</td>
</tr>
<tr>
<td>Night average</td>
<td>91.3</td>
<td>91.0</td>
<td>93.0</td>
<td>91.7</td>
<td>90.8</td>
<td>87.9</td>
<td>91.1</td>
<td>89.3</td>
<td>91.4</td>
<td>92.3</td>
<td>95.3</td>
<td>92.5</td>
<td>91.5</td>
</tr>
<tr>
<td>Day average</td>
<td>83.3</td>
<td>82.6</td>
<td>84.1</td>
<td>82.6</td>
<td>83.3</td>
<td>81.0</td>
<td>82.7</td>
<td>81.2</td>
<td>83.1</td>
<td>84.4</td>
<td>88.5</td>
<td>85.9</td>
<td>83.6</td>
</tr>
<tr>
<td><strong>Wind speed m/s</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work average</td>
<td>5.0</td>
<td>4.2</td>
<td>2.7</td>
<td>2.3</td>
<td>2.9</td>
<td>3.1</td>
<td>3.0</td>
<td>3.8</td>
<td>2.8</td>
<td>2.5</td>
<td>2.4</td>
<td>3.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Night average</td>
<td>2.5</td>
<td>1.8</td>
<td>0.6</td>
<td>0.3</td>
<td>0.8</td>
<td>1.6</td>
<td>1.2</td>
<td>1.3</td>
<td>0.8</td>
<td>1.3</td>
<td>0.5</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Day average</td>
<td>3.9</td>
<td>3.1</td>
<td>1.7</td>
<td>1.3</td>
<td>1.7</td>
<td>2.3</td>
<td>2.1</td>
<td>2.5</td>
<td>1.8</td>
<td>1.7</td>
<td>1.4</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Sky cover %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work average</td>
<td>87.4</td>
<td>85.3</td>
<td>84.0</td>
<td>83.4</td>
<td>83.0</td>
<td>85.1</td>
<td>83.3</td>
<td>87.7</td>
<td>85.9</td>
<td>87.7</td>
<td>90.5</td>
<td>89.0</td>
<td>86.0</td>
</tr>
<tr>
<td>Night average</td>
<td>85.2</td>
<td>87.7</td>
<td>84.4</td>
<td>86.0</td>
<td>81.3</td>
<td>82.4</td>
<td>86.1</td>
<td>85.1</td>
<td>85.2</td>
<td>87.7</td>
<td>89.1</td>
<td>87.6</td>
<td>85.6</td>
</tr>
<tr>
<td>Day average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rainfall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean monthly [mm]</td>
<td>240</td>
<td>159</td>
<td>184</td>
<td>178</td>
<td>172</td>
<td>160</td>
<td>158</td>
<td>176</td>
<td>168</td>
<td>193</td>
<td>255</td>
<td>288</td>
<td>2331</td>
</tr>
<tr>
<td>Rain [days]</td>
<td>15</td>
<td>11</td>
<td>14</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td>14</td>
<td>16</td>
<td>19</td>
<td>19</td>
<td>178</td>
</tr>
</tbody>
</table>

**Potential cooling techniques for Singapore**

Cooling techniques discussed in paragraph 3.2 are not all applicable in all climates. The climate shows very low diurnal differences and no seasonal differences. Combined with all year high all day high humidity and high temperatures makes this a challenge to reduce cooling load reduction. Advantage or disadvantage can be the cloudiness, as the daylight is diffuse and causing an increase in outdoor temperature.

#### Table 3.2 evaluation cooling techniques for Singapore

<table>
<thead>
<tr>
<th>Cooling technique</th>
<th>Environmental requirements</th>
<th>Singapore Climate</th>
<th>Evaluation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic</td>
<td>Low humidity level</td>
<td>RH work average 76%</td>
<td>-</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Day night or seasonal</td>
<td>Ground temperature = DRB av. = 27.5°C</td>
<td>-</td>
</tr>
<tr>
<td>Dehumidification; Refrigerate</td>
<td>Cold water</td>
<td>Ground water temperature = DRB av. = 27.5°C</td>
<td>-</td>
</tr>
<tr>
<td>Dehumidification; Desiccant</td>
<td>Heat is required to</td>
<td>DRB av. 27.5°C + (passive?)</td>
<td>+</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>Only effective during</td>
<td>DRB av. 27.5°C +</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>daytime, wind,</td>
<td>Wind work av. 3.2m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>prevailing direction, temperature</td>
<td>Prevailing North south direction</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------</td>
<td>----------------------------------</td>
<td></td>
</tr>
<tr>
<td>Night time ventilation</td>
<td>lower external air temperatures at night</td>
<td>ΔT=5.0°C</td>
<td></td>
</tr>
<tr>
<td>Phase change materials</td>
<td>Temperature differences</td>
<td>ΔT=5.0°C</td>
<td></td>
</tr>
<tr>
<td>Thermal mass</td>
<td>Temperature differences, more than 10 degrees</td>
<td>ΔT=5.0°C</td>
<td></td>
</tr>
<tr>
<td>Solar shading</td>
<td>shading can prevent the building form overheating</td>
<td>150 – 450 kWh/m2 façade. Clouds diverging radiation</td>
<td>+</td>
</tr>
<tr>
<td>Daylight</td>
<td>daylight is scattered by the clouds.</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

*The evaluation in will be further explained in the next paragraphs.*

### Adiabatic cooling

Current HVAC systems dehumidify the air till levels below 60% with an average humidity level in Singapore during the work day of 76%RH it leaves not a lot of space for extra moisture. The efficiency of adding extra moisture in a humid environment is questionable as well as there will be large quantities of water needed. As rain occurs almost every day and normal in the afternoon it is the question if it even will work in this environment.

### Thermal mass

**Geothermal energy**

The use of a heat sink in the ground has great potential for buildings in temperate climate where there are diurnal and seasonal temperature differences that can charge and discharge the ground. For the tropical environment of Singapore the expectation is that the groundwater is the average yearly temperature. This temperature is above 25 degrees and leaving little space for high heat absorbing capacity.

**PCM and thermal mass**

Other techniques that require temperature differences to charge and discharge are thermal mass and phase change materials. Both have the ability to function well in temperate climates, but will have little or none effect in Singapore. The concrete mass of the office may be able to function as heat sink in the mornings, but this will be for limited amount of time. PCM can have influence in the ventilation system, but as an extra measure to challenge efficiency. On its own it is not possible to function due to the lack of temperature differences.

### Nighttime ventilation
Dehumidification

Desiccant

rainfall the temperature drops, what makes it more comfortable. The high humidity during these rains makes it uncomfortable, by dehumidifying this incoming air, the air can be comfortable. In current HVAC systems the air is dehumidified with desiccant wheel. The disadvantage of this system is the required heat to regenerate the desiccant. Discharging can be done via collected heat on the roof of the building, or via the façade. This will bring extra energy consumption, something we want to reduce, but can reduce the cooling load. The regeneration can be done via solar systems. This is an effective solution as long as the outside temperature is not too high.

Refrigerate

This solution is only possible when there is a large difference in surface water temperature and surrounding air. As the groundwater is warm on its own, this way of distracting humidity cannot be very successful.

Natural ventilation

Natural ventilation seems to be effective for the climate of Singapore. While it is not able to tackle the humid conditions it is able to remove the excessive heat with the natural flow. The prevailing wind direction can be used to design the façade that maximize the wind collection from north-south direction.

For Singapore the natural ventilation is investigated by Haase and Amato. They found that the potential for natural ventilation improvements can be up to 43%. This doesn’t refer to offices directly, but can indicate that there is potential energy saving possible in a tropical climate by natural ventilation (Haase & Amato, 2009).

Solar shading

Solar shading is an effective measure to reduce internal heat load. It can be used in combination with the other strategies. It will interfere with air flows and the visual
comfort. Even with the relative low amount of radiation in Singapore, it will be successful to have external sun shading.

**Daylight**

The effect of daylight cooling will be very small with current LED techniques, but it can still be used as extra asset. With extra daylight entrance indoor environment will improve what can be positive for the occupant’s experience.

### 3.4. Conclusion on local climate

The climate in Singapore is one of the most challenging climates with high temperatures and low diurnal differences. High HVAC demand and settings make it hard to compete with an effective passive or less energy demanding solution. Lack of temperature differences in day and night temperature, below the 10 degrees, thermal mass in combination with night time ventilation are not sufficient. For geothermal energy the average high temperature is insufficient to use to function as a heat sink. With ground water around the average daily temperature there won’t be cold water in the soil to use with a heat pump.

Natural ventilation seems to be the only effective technique. In combination with bioclimatic design, shading and daylight savings it is the best combination to improve energy efficiency in Singapore.

As discussed in chapter 2, the mixed mode strategy will be a good solution to combine the passive natural ventilation technique in combination with a bioclimatic design and an electrical climate system. Thermal comfort in the next chapter will discuss the possible comfortable temperatures inside the office to reduce the amount of operable hours for the hybrid system.

*Figure 3.18 Kwh/m2/year for each orientation between 9:00 and 18:00 (3650 hours) with 0,2 reflection factor (Normal Horizontal radiation is 1646 Kwh/m2/year). Climate consultant Singapore*
FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE
4. THERMAL COMFORT

Energy-efficient buildings are only effective when the occupants of the buildings are comfortable. If they are not **COMFORTABLE**, then they will take alternative means of heating or cooling a space such as space heaters or window-mounted air conditioners that could be substantially worse than typical Heating, Ventilation and Air Conditioning (HVAC) systems.

The alternative to the air-tight, sealed box building are buildings that can be opened and interact with their environment and provide better comfort conditions while reducing the dependence on energy intensive HVAC systems. The issue of providing thermal comfort in buildings has been always a major issue in building design. Before the cost of energy became an important factor, building design was carried out with little attention to the energy consumed in running the building and meeting the thermal comfort and air quality needs of the occupants. This gave rise to problems like **SICK BUILDING SYNDROME** and reduced employee **PRODUCTIVITY** (Ogwezi, Jeronimidis, Cook, Sakula, & Gupta, 2012).
Thermal comfort is difficult to measure because it is **HIGHLY SUBJECTIVE**, and is defined as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 2013). Thermal comfort, or human comfort, is thus the occupants’ **SATISFACTION** with the surrounding thermal conditions and is essential to consider when designing a truly energy efficient building that will be occupied by people.

### 4.1. Thermal sensation

A cold sensation will be pleasing when the body is overheated, but unpleasant when the core is already cold. At the same time, the temperature of the skin is not uniform on all areas of the body. There are variations in different parts of the body which reflect the variations in blood flow and subcutaneous fat. The insulative quality of clothing also has a marked effect on the level and distribution of skin temperature. Thus, sensation from any particular part of the skin will depend on time, location and clothing, as well as the temperature of the surroundings.

#### Heat transfer of the human body

Thermal comfort is calculated as a heat transfer energy balance. The body’s thermal balance can be expressed as (Auliciems & Szokolay, 2007)

\[
M \pm R \pm Cv \pm Cd - E = \Delta S
\]

If $\Delta S$ is positive, the body temperature increases, if negative it decreases. The heat transfer occurs between the environment and the human body, which has an average area of 1.7 m² (ASHRAE, 2013; Busato, 2003). Heat transfer through evaporation, radiation, convection, and conduction are balanced against the occupant’s metabolic rate. The heat dissipation rate depends on environmental factors, but can also be influenced by several physiological regulatory mechanisms.

#### Sensible heat loss

There are three sensible heat loss mechanisms: Radiant loss to cooler surfaces (or gain from warmer surfaces); Convection loss to cooler air (or gain from warmer air) which is heated and rises; and dry respiration heat loss to cooler air that enters the lungs and is exhaled warmer.

Sensible heat exchange from the skin must pass through clothing to the surrounding environment. These paths are treated in series and can be described in terms of heat
transfer from the skin surface, through the clothing insulation, to the outer clothing surface, and from the outer clothing surface to the environment. Both convective and radiative heat losses from the outer surface of a clothed body can be expressed in terms of a heat transfer coefficient and the difference between the mean temperature of the outer surface of the clothed body and the appropriate environmental temperature (ASHRAE, 2013). Generally, the faster the flow of air around the body, the thinner the boundary layer of air on the body’s surface, and hence the lower the thermal insulation afforded the subject (J. R. de Dear, Arens, Hui, & Oguro).

Table 4.1 Estimated radiative and convective heat transfer coefficients for seated nude thermal manikins. (J. R. de Dear et al., 1996)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Radiative heat transfer Coefficient (W/m² per K)</th>
<th>Convective heat transfer Coefficient (W/m² per K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Chest</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Upper arm/shoulder</td>
<td>4.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Back</td>
<td>4.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Pelvis</td>
<td>4.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Forearms</td>
<td>5.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Hands</td>
<td>3.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Thighs</td>
<td>4.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Lower legs</td>
<td>5.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Foot L+R</td>
<td>4.5</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Values for convective and radiative heat losses for nude manikins are shown in the table above. Research by Sørensen & Voigt confirms that head, forearms, hands, lower legs and feet are good places for heat transfer in means of convective and radiative heat loss in tropical climates where people wear less insulative clothing (2003).

Figure 4.1 Figure 4.2 Sensible heat loss mechanisms. Own illustration
Evaporative heat loss

The latent heat loss mechanisms include: latent respiration heat loss, water diffusion through the skin, and the evaporation of sweat typically expressed with skin wittedness (ASHRAE, 2013). Depending on the amount of moisture on the skin and the difference between the water vapour pressure at the skin and in the ambient environment (ASHRAE, 2013). High relative humidity can interfere with the loss of moisture from the skin due the level of air saturation making it more difficult for the body to reduce its temperature (Ogwezi et al., 2012).

Factors in thermal comfort

Fanger describes six different variables for defining the “product” of thermal comfort, which is produced and sold to the customer of the building (1972, p. 15). They can be divided in four environmental parameters: Air temperature, mean radiant temperature, air flow rate and humidity, and two personal parameters; activity and clothing level (Jai Kanth, 2005).

Air temperature

The air temperature is the average temperature of the air surrounding the occupant. An accumulation of air temperature at ankle, waist and head levels, which are different for seated or standing occupants. Air temperature is measured with a dry-bulb thermometer and for this reason it is also known as dry-bulb temperature (DBT).

Relative humidity

Relative humidity (RH) refers to the amount of moisture in the air as compared to the maximum amount of moisture the air can hold at a particular temperature and is normally equally divided over the room (Fanger, 1972, p. 142). It gives an indication of how much moisture the air can take up from a person’s skin through perspiration.

Recommended level of indoor humidity is in the range of 30-60% in air conditioned buildings. New standards allow lower and higher humidity, depending on the other factors involved in thermal comfort. In research by Nicol the water vapour pressure was
measured instead of the relative humidity. In the 22 surveyed buildings the difference is within a maximum of one degree. Concluding that there is no relevant difference in the comfort temperatures in naturally ventilated buildings for outdoor with temperatures between 20°C and 30°C due to the influence of humidity (F. Nicol, 2004).

In the humid tropics people might not to be affected by the variation of relative humidity. Perception of comfort is influenced by long-term conditioning to high temperatures and humidity. Clothing and personal habits are influenced by exterior conditions, as are expectations of comfort (Djamila, Chu, & Kumaresan, 2014).

![Figure 4.2 The effect of mean water vapour pressure (pa) on comfort temperature (F. Nicol, 2004).](image)

![Table 4.2 Range and mean value for the 3-tiles of outdoor relative humidity (RHO) and water vapour pressure (pa) (F. Nicol, 2004).](table)

<table>
<thead>
<tr>
<th>Relative humidity (%)</th>
<th>Water vapour pressure Pa (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>1</td>
<td>&lt;63</td>
</tr>
<tr>
<td>2</td>
<td>64-75</td>
</tr>
<tr>
<td>3</td>
<td>&gt;75</td>
</tr>
</tbody>
</table>

**Mean radiant temperature**

The mean radiant temperature (MRT) reflects the radiance of surfaces in relation to the human body, and is therefore different for each occupant and hard to measure precisely (Fanger, 1972, p. 141). MRT is defined as the uniform temperature of an imaginary black enclosure (office buildings have building materials with high emittance; so all surfaces in the room can be assumed to be black) (Fanger, 1972, p. 143; Innova, 2002).
An accurate method, but requires a considerable amount of calculation work, is to use the temperature of surrounding walls and surfaces and their positions in relation to the occupant (Fanger, 1972, p. 141). Another and more common way is to use the combination of the globe temperature, air temperature, and air velocity can be used to estimate the mean radiant temperature (ASHRAE, 2013).

**Air flow rate**

A high air velocity will increase convective heat transfer and evaporative heat loss from the human body and will prevent thermal discomfort due to moist skin, which enhances physiological cooling and thus induces thermal comfort (Prajongsan & Sharples, 2012). The effectiveness of higher air movement to compensate for high air temperatures has been investigated and confirmed in previous studies in Thailand and Singapore (Baruch Givoni, 2011).

![Figure 4.3 Comfortable temperature tested in climate chamber with 16 subjects. RH and selected air speeds against the ASHRAE comfort zone at 60% and 80% RH with elevated air movement. With 0.5 Clo and 1.1 met. (Zhai et al., 2013)](image)

Higher air speeds (up to 3 m/s) are preferred by subjects in Thailand and Hong Kong at temperatures higher than 30 °C and at RH values as high as 85%. If occupants have control, comfort could be maintained at 31 °C with 50% RH and 1.6 m/s air speed, and at 29 °C, 80% RH with 1.4 m/s air speed. They prefer a cooler-than-neutral thermal sensation if possible by selecting an average higher air speed (Zhai et al., 2013).
Figure 4.3 shows the chamber experiment where sixteen human subjects were exposed to personally controlled air movement provided by floor fans in a climate chamber. The study confirms high air speeds can be desirable and have direct influence on the comfort.

The air speeds chosen by the subjects for this study's temperature–humidity combinations are shown in the figure above. At temperatures near 28 and 30 °C air speeds of 1.8 m/s are practical, but may not be sufficient for the combination of 30 °C/80% RH (Zhai et al., 2013).

Metabolic rate

Metabolic rate is the heat generated by the body depending on the level of physical activity being performed. About 75% of the energy consumed by the body ends up in the form of heat which heats up the body (ASHRAE, 2013). Metabolic rate is normally measured in Met \((1 \text{ Met} = 50 \text{ kcal/h}\times\text{m}^2 = 58.15 \text{ W/m}^2)\). A normal adult has a surface area of 1.7 m², and a person in thermal comfort with an activity level of 1 Met will thus have a heat loss of approximately 100W. Metabolic rate varies between individuals according to their age and sex. The following are some examples of estimated values of metabolic rate for different activities:

<table>
<thead>
<tr>
<th>Office activities</th>
<th>met*</th>
<th>Resting activities</th>
<th>met*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading, seated</td>
<td>1.0</td>
<td>Sleeping</td>
<td>0.7</td>
</tr>
<tr>
<td>Writing</td>
<td>1.0</td>
<td>Reclining</td>
<td>0.8</td>
</tr>
<tr>
<td>Typing</td>
<td>1.1</td>
<td>Seated, quiet</td>
<td>1.0</td>
</tr>
<tr>
<td>Filing, seated</td>
<td>1.2</td>
<td>Standing, relaxed</td>
<td>1.2</td>
</tr>
<tr>
<td>Filing, standing</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking about</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifting/packing</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clothing

Clothing reduces the body’s heat loss and it influences the thermal comfort sensation. The unit used to measure clothing’s insulation is Clo \((1 \text{ Clo} = 0.155 \text{m}^2\text{°C}/\text{W})\) (ASHRAE, 2013). Complete nude means no insulation value and Clo value is zero. Below are possible ensembles for man and women. In the appendix there is more a detailed list.

<table>
<thead>
<tr>
<th>Ensemble description Men</th>
<th>Clo</th>
<th>Ensemble description Women</th>
<th>Clo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking shorts, short sleeved shirt</td>
<td>0.36</td>
<td>Knee-length skirt, short-sleeved shirt, panty, hose, sandals</td>
<td>0.54</td>
</tr>
</tbody>
</table>
4.2. Predicting thermal comfort

Thermal comfort standards help building designers to provide an indoor climate that building occupants will find thermally comfortable. The definition of a good indoor climate is important to the success of a building, not only because it will make its occupants comfortable, but also because it will decide its energy consumption and thus influence its sustainability (J. F. Nicol & Humphreys, 2002).

Theory of Fanger

A method of describing thermal comfort was developed by Ole Fanger in the 70’s and is referred to as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). As of today large parts of the thermal comfort research is based on the theories of Fanger.

The Predicted Mean Vote (PMV) refers to a thermal sensation scale that runs from Cold (-3) to Hot (+3). The original data was collected by subjecting a large number of people to different conditions within a climate chamber and having them select a position on the scale the best described their comfort sensation.

*Table 4.4 Comfort scales (Auliciems & Szokolay, 2007)*

<table>
<thead>
<tr>
<th>Value</th>
<th>ASHRAE</th>
<th>Bedford</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>Cold</td>
<td>Much too cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
<td>Too cool</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
<td>Comfortably cool</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
<td>Comfortable</td>
</tr>
<tr>
<td>1</td>
<td>Slightly warm</td>
<td>Comfortably warm</td>
</tr>
<tr>
<td>2</td>
<td>Warm</td>
<td>Too warm</td>
</tr>
<tr>
<td>3</td>
<td>Hot</td>
<td>Much too warm</td>
</tr>
</tbody>
</table>
Neutral temperature

Skin temperature is standard around 32 degrees and the human body is an intelligent system to control this. With the help of appropriate clothing we can feel comfortable in a broad range of temperatures. Although thermal sensation is a subjective measurement. For building design it is the task to account the comfort level for several occupants instead of only one. The neutral temperature is the middle of thermal sensation of a group where 50% feels cold and 50% warm.

Predicted Percentage of Dissatisfied

The number of people dissatisfied with their comfort conditions is 100%, as you can never please all of the people all of the time, the recommended acceptable PPD range for thermal comfort from ASHRAE is less than 10% persons dissatisfied for an interior space (2013).

Comfort zone

A comfort zone is a range of operative temperatures and relative humidity values that allow for a certain percentage of individuals would be dissatisfied with. This zone is also defined by the level of clothing and metabolic rate of the individuals (Ogwezi et al., 2012).

A comfort zone of 2–3°C either side of the optimum can be taken as acceptable. If fans are available to building occupants can add another 2 °C to the predicted comfort temperature in hot conditions. In a humid climate or in conditions when the relative humidity is high people may require temperatures that are about 1 °C lower to remain comfortable, but the main effect of a higher humidity (or water vapour pressure) is to reduce the width of the comfort zone (F. Nicol, 2004).

Operative temperature

In design, operative temperature can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients (ASHRAE, 2013).

Thermal comfort indexes

The theory of Fanger does not adequately describe comfort conditions when buildings are not mechanically heated or cooled (F. Nicol, 2004). Currently there are three international standards that have been used widely in the indoor building environment, which are ANSI/ASHRAE Standard 55 (2013), ISO standard 7730 (2005) International standard and CEN Standard EN15251 (2007).
These standards cannot cope with all the different climates in one model e.g. ISO7730, based on Fanger’s PMV, overestimates the occupant response on the ASHRAE scale when there are high outside temperatures and underestimates it with low outside temperatures (Liping & Hien, 2007). As a result it predicts discomfort in cases which subjects in field surveys find comfortable and underestimates the range of temperatures which people find comfortable.

Adaptive thermal comfort

For this thesis the adaptive thermal comfort model is used. Specifying the acceptable indoor environment in relation to the monthly mean outdoor air temperature as an index for occupants’ adaptation to outdoor conditions. They assume that, if changes occur in the thermal environment that produces discomfort, then people will change their behaviour and act in a way that will restore their comfort. Such actions could include taking off clothing, reducing activity levels or even opening a window.

The model considers clothing adaptation of the occupant in naturally ventilated spaces by linking the acceptable range of indoor temperatures to the outdoor climate (Table with adaptive behaviour is in the Appendix). Therefore it is not necessary to estimate the clothing values. Furthermore, humidity and limits of air-speed are not required.

A large number of field studies were conducted to correlate the outdoor temperature with the indoor thermally comfortable conditions for free running buildings. The field studies show that indoor thermal neutrality and comfort range have strong statistical dependence on the mean outdoor temperature. To get a good prediction model what can be functional in Singapore the field surveys in similar climates are relevant.

Figure 4.4 Figure 4.5 Adaptive model is shown by the blue comfort line. The red line shows the comfort temperatures for none free-running buildings without adaptive model. The orange line is based on the research in climate chambers (Brager & de Dear, 2001).
Humphrey

Humphrey quantified two relationships, one for buildings where heating or cooling (HC) was in use at the time of the comfort survey and the free running mode (FR). It was a classification of mode of operation rather than of type of building. The correlation in the FR mode was found to be linear and surprisingly strong (coefficient of correlation $r = 0.97$). The equation of the regression line is (Michael Humphreys, 1978);

\[
T_n = 11.9 + 0.534 \cdot \overline{T_O}
\]

Where $T_n$ is the predicted neutral temperature and $\overline{T_O}$ the monthly mean outdoor temperature, derived from the mean maximum and the mean minimum of the metrological records (F. Nicol, 2004). The range of application is from 10° - 33°C (Michael Humphreys, 1978).

Auliciems

Auliciems continued with Humphreys model and updated the database (MA Humphreys, Rijal, & Nicol, 2013). With the new data Auliciems gained a new regression line with a linear relation (MA Humphreys et al., 2013);

\[
T_n = 17.7 + 0.27 \cdot T_O
\]

This line is lower than the one of Humphreys for the FR mode but higher than for the HC mode. This due to the fact that there is no separation of FR and HC mode. Unfortunately this is only for comfort temperatures of 18 till 28°C.

The problem with using a single line to represent the two modes of operation is that its regression gradient would depend upon the relative number of surveys in the database in either mode of operation. It is necessary to keep the distinction between the modes of operation. However he did find that indoor temperatures should be ‘thermobile’ with variable set-point in relation to the outdoor temperature, rather than a ‘thermostat’ with a fixed set-point (MA Humphreys et al., 2013).

Nicol

In a field study in Pakistan a similar equation (EQ 4) is developed with the relation between neutral temperature and outdoor temperature (Sedki, Hamza, & Zaffagnini, 2013).

\[
T_n = 17 + 0.38 \cdot T_O
\]
In another survey in Pakistan they suggested (J. Fergus Nicol, Raja, Allaudin, & Jamy, 1999):

\[ T_n = 18.5 + 0.36 \cdot T_O \]

De Dear

De Dear and Brager (2001) recommended the model that is based on the relation between the mean monthly outdoor temperature and the neutral temperature.

\[ T_n = 17.8 + 0.31 \cdot \overline{T}_O \]

The mean monthly temperature is calculated as the average of the full month with 24-hour input. The temperature upper and lower limits are defined by the following formulas:

- Upper 80% acceptable limit (°C) = 0.31 \cdot (outdoor air temperature) + 21.3
- Upper 90% acceptable limit (°C) = 0.31 \cdot (outdoor air temperature) + 20.3
- Lower 80% acceptable limit (°C) = 0.31 \cdot (outdoor air temperature) + 14.3
- Lower 90% acceptable limit (°C) = 0.31 \cdot (outdoor air temperature) + 15.3

The 80% and 90% acceptability limits should flatten out at mean monthly outdoor air temperatures warmer than 32°C or cooler than 5°C (R. de Dear & Brager, 2001).

Comfort for Singapore

However, the adaptive comfort models for naturally ventilated buildings still needs more development to combine all environmental and personal factors that affect thermal comfort. Equation (EQ 6) is adopted for this thesis. This model is more applicable and accurate than the one which based on the effective temperature and was adopted by ASHRAE standards (Sedki et al., 2013).

With the temperature limit of 10%PPD it is the same level to satisfy office occupants according the Ashrae 2010. This gives the overview of the hours of discomfort in the outdoor temperature.
Figure 4.5 Comfortable hours per month with adaptive thermal comfort of ASHRAE for 24H days

Amount of hours uncomfortable is almost equal per month. Due to the day differences per month the height of the column is 744 (31 days) or 720 hours (30 days), with exception for the month of February which has 672 hours (28 days).

Figure 4.6 Comfortable hours of the day with adaptive thermal comfort of ASHRAE for 24H days

The graphic represents each working hour for the 365 days in year. The working day starts at 8:00 hour and finishes at 19:00. In case occupants want to continue working there should be a possibility, but this is not included in the calculation. During the afternoon a heat peak occurs, starting at 11:00 till 18:00. The difference in the first two peak hours can be balanced with thermal capacity of the construction, but for 13:00 – 17:00 there is an obvious problem.

Air movement

It is common experience that air movement, be it a natural wind, or generated by a fan, has a cooling effect. This largely depends on the velocity of that air movement to allow
an equivalent with what the comfort temperature can be raised. The effect of air movement is two-fold: the convection heat loss coefficient of the body is a function of air velocity, but evaporation from the skin, thus the evaporation heat loss coefficient is also increased by moving air. An additional effect is that with no movement a practically saturated air layer is formed at the body surface, which prevents (reduces) further evaporation. Air movement would remove this saturated air envelope (Auliciems & Szokolay, 2007).

Table 4.1 Average subjective reactions to various velocities (Auliciems & Szokolay, 2007)

<table>
<thead>
<tr>
<th>Air speed</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.25 m/s</td>
<td>unnoticed</td>
</tr>
<tr>
<td>0.25-0.50 m/s</td>
<td>pleasant</td>
</tr>
<tr>
<td>0.50-1.00 m/s</td>
<td>awareness of air movement</td>
</tr>
<tr>
<td>1.00-1.50 m/s</td>
<td>draughty</td>
</tr>
<tr>
<td>&gt; 1.50 m/s</td>
<td>annoyingly draughty</td>
</tr>
</tbody>
</table>

These reactions however, depend on the temperature of the air. Under hot conditions 1 m/s is pleasant and indoor air velocities up to 1.5 m/s are acceptable (for practical reasons). Above this, light objects may be blown about, thus indirect nuisance effects may be created.

In tropical climates air movement will be an important factor in determining comfort. Where the air velocity above 0.1 m/s and fairly constant will increase the comfort temperature up to a maximum of 2 degrees. by (F. Nicol, 2004):

\[
T_n = T_c + 7 - \frac{50}{4 + 10 \cdot v^{0.5}} \text{ [°C]} \text{ max 2 °C}
\]

The ASHRAE Handbook of Fundamentals allows an extension of the upper comfort limits with 1 degree for every 0.275 m/s air velocity above 0.2 m/s (maximum up to 0.8 m/s equal to 2 °C) (Auliciems & Szokolay, 2007). Givoni suggests that for warm climates this should be extended to 2 m/s (maximum up to by 6 °C) (Auliciems & Szokolay, 2007).

\[
T_n = T_c + \left(\frac{v^{0.2}}{0.275}\right) \text{ [°C]} \text{ max 2 – 6 °C}
\]

For offices the limit should be the discomfort level. When papers are flying around the environment is disturb, therefore the addition of Givoni cannot be used for professional environments. The addition can be useful for residential and recreational usage.
Local discomfort

A person may feel thermally neutral as a whole but still feel uncomfortable if one or more parts of the body are too warm or too cold. This local discomfort can be due to a cold window, warm surface, air flow or other changes. Even small changes in heat flow cause the thermal regulatory system to compensate by increasing the physiological effort of maintaining body temperatures (ASHRAE, 2013).

Draught

Naturally ventilated buildings must provide enough air exchange under a large variety of outdoor and indoor conditions from favourable to very unfavourable conditions (e.g. low wind speeds, small temperature differences, etc.). Under these latter circumstances, relatively large openings may be required. Unless automatic controls are provided it is impossible for occupants to respond to the normal rapid fluctuations in outdoor conditions and act to limit large air exchange rates alternating with smaller one. Even with automatic control, the system may not be able to deal with the fast changes in outdoor conditions. When the air exchange is large enough, air velocities indoors may become larger than desired and cause uncomfortable. If they are strong enough, draughts may even move papers and other light objects from their desired positions, something that is usually unacceptable, both in residences and in offices (Allard, 1998).

Fanger describes draught as a function of the general state of mind: “If a person feels warm he is likely to assess a local convective cooling as pleasant while the same draught might be felt unpleasant if he feels cool” (1972, p. 100). Therefore in tropical climates people tolerate higher wind velocities than in temperate or cold climates.

Vertical air temperature difference

In most buildings, air temperature normally increases with height above the floor. If the gradient is sufficiently large, local warm discomfort can occur at the head and/or cold discomfort can occur at the feet, although the body as a whole is thermally neutral (ASHRAE, 2013).

Figure 4.7 Vertical temperature gradient (ASHRAE, 2013).
Heat accumulation

Occupants produce heat, appliances and solar radiation if shading is not proficient. This will accumulate heat in the space and reduce the comfort. With the application of the 10%PPD and the adaptive thermal comfort model, it leaves 404 office working hours where the outdoor temperature is still comfortable (with 80%RH limit). When interior temperature raises the comfort level will reduce fast. With one degree higher the temperature is only comfortable for 87 hours, and for 2 degrees difference it is almost zero. Therefore air should be removed as fast as possible to maintain comfort close to 400 hours. With extra airflow this can be compensated.

Table 4.1 Heat accumulation in the office, figure 4.7 is a visualization of the values.

<table>
<thead>
<tr>
<th>Hours of HVAC saving &amp; heat accumulation</th>
<th>Outdoor temperature</th>
<th>Outdoor +1</th>
<th>Outdoor +2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours comfortable 10%PPD</td>
<td>404</td>
<td>87</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 4.8 Heat accumulation is a thread for the cooling load reduction. Indoor conditions (10% dissatisfied) temperature + humidity limit.

4.3. Conclusion on thermal comfort

It is in principle possible to design and operate buildings that provide comfort in the free-running mode at least within a range of prevailing mean outdoor temperature from 10 to 30 °C.
Thermal comfort models define what an acceptable and thus comfortable climate is. It is mainly based on the research of Fanger, and later on the adaptive thermal comfort models to achieve a broader application. In the adaptive approach for offices clothing and activity are less relevant as it is possible for individuals to adapt to situations to stay comfortable.

Humidity up to 80% has no direct influence on the temperature experience. High humidity can be for corrected via the comfort zone as it is not part of the adaptive thermal comfort. The comfort zone can be one degree smaller to compensate for high humidity.

Other discomfort factors can influence the thermal sensation; this should be prevented as there are only 404 hours in which the temperature is comfortable without air movement with a 10%PPD. To improve comfort extra movement is a necessity, and a backup system should be available to create a comfortable environment for the remaining 89%. Airflow can increase the comfort temperature up to 2 degrees, but is limited by draught.

Normally adaptive models imply the expectations of the weather; current condition is in relation with previous days. For big companies, indoor climate is something that is used as a show off, a signal of prosperity. In the international financial and other business sectors of Singapore office workers are used to the 22 degrees and low relative humidity, a typical European climate, during working hours.

Although these workers may live in natural ventilated homes, with even higher humidity levels than during the day, they adapt themselves in order to fit in the ‘real’ business culture. To manage the energy consumption, the system should be able to cope with this habit in company culture. If the design is not able to deal with the expectation, occupants will bring small cooling devices in order to cool down their offices. Making the whole building less energy efficient.
Ventilation is generally defined as the supply of outside air to the interior for air movement and replacement of stale air by fresh air for a healthy and comfortable indoor environment. There are two types of ventilation systems. Natural and mechanical ventilation systems. Natural ventilation is one of the promising cooling techniques to challenge the climate of Singapore. This chapter will deal with two types of natural ventilation strategies in general, the cross ventilation based on wind and the stack effect of the solar radiation.
5.1. Principles of natural ventilation in a high-rise building

The driving forces for natural ventilation in a tall building are the same as those for other buildings. The physical mechanisms for natural ventilation rely on the pressure differences generated across the envelope openings of a building. The pressure differences are generated by:

- The effect of wind
- Temperature differences between inlet and outlet (gravitational force)
- Combination of both

Natural ventilation can therefore be summed by two categories; wind- and buoyancy induced ventilation. **WIND INDUCED VENTILATION** occurs when wind creates a pressure distribution around a building with respect to the atmospheric pressure. The pressure differences drive air into the building envelope on the windward side (positive pressure zone) and out of the building through the openings on the leeward side (negative pressure side). The pressure effect of the wind on a building is primarily dominated by the building’s shape, the wind direction and the velocity of the wind, and the influence of surrounding objects. Which are all factors that influence the pressure coefficient, the mean pressure difference across a buildings envelope is dependent upon the mean wind velocity at upwind building height, and the indoor air density as a function of atmospheric pressure, temperature and humidity (Wood & Salib, 2013).

Buoyancy-induced ventilation, or **STACK-EFFECT**, occurs due to density differences caused by variations in temperature and height between the inside and the outside or between certain zones within a building. The pressure differences generated by buoyancy are mainly dependant on the difference in height between intake and outlet and the temperature difference of the air. To guarantee inward airflow in the absence of wind, it is important to ensure that outdoor temperatures are lower than indoor temperature to achieve buoyancy induced-

---

*Figure 5.1 Thermal buoyancy in tall buildings.* (Wood & Salib, 2013)
ventilation. When the indoor temperature exceeds the outdoor temperature an under pressure is formed in the lower part of a building, pulling air inwards through the openings in the envelope.

The density difference is caused by the indoor/outdoor temperature difference results in a different pressure gradient in the building. The over pressured zones at the top of the building drive air out of the openings in the building since air flows from areas of high pressure to areas of low pressure. At a certain level of the building, the indoor pressure and the outdoor pressure are equal to each other. This level is referred to as the “neutral plane” or “neutral pressure level”. In order to achieve effective buoyancy-induced ventilation, there has to be a significant temperature difference between inlet and outlet of air, and minimal internal resistance to air movement within the interior spaces. The opposite effect, REVERSE STACK EFFECT can occur if the outside air is significantly warmer than the inside air. Under this condition the air can enter high-rise buildings at high elevations and is difficult to manage (Wood & Salib, 2013).

Wind and buoyancy can occur separately, but more likely is the two driving forces for natural ventilation occur at the same time. Thermal buoyancy will generally be the dominating driving force on a calm day with practically no wind, whereas pressure differentials generated by wind will typically be the dominating driving force on a windy day (Wood & Salib, 2013).

**Natural ventilation strategies**

A “ventilation strategy” refers to how air is introduced into a building, and how it is extracted out of it (Wood & Salib, 2013). As in low-rise buildings, there are different strategies used to ventilate high-rise buildings can be classified into three main categories:

I Single-sided ventilation

This is usually the simplest form of naturally ventilating a building whereby the fresh air enters the room through the opening on the same side as it is exhausted from. Although this is a very common and inexpensive system it is uncontrollable, except in an open or closed position, and can only be effective over a distance of about six meters from the opening itself (Hazim B Awbi, 1994). In rooms with more height this strategy can be still effective if the room depth is a maximum of 2.5 times the height (Wood & Salib, 2013). The driving force for single-sided ventilation is wind coinciding with the temperature difference between low-level air inlets and high-level air outlets. Buoyancy effect can also aid single-sided ventilation if the ventilation openings are located at different heights. Furthermore some single-sided opening, e.g. windows are only suitable in moderate climates and are not suitable for winter ventilation.
II Cross-ventilation

For spaces deeper than six meters the strategy of a two-sided or cross-flow ventilation can be applied. This usually implies using the same openings as those used for a single-sided ventilation system but these are installed on two or more opposite walls. This method can be used in spaces where the depth is up to five times the height of the room. It is more effective than single-sided ventilation because the wind pressure can be more favourable for providing larger air flow rates. The buoyancy effect can also aid the effectiveness of cross ventilation when the spaces are facing a tall open space such as an atrium (Wood & Salib, 2013). However this method also suffers from the same problems of air flow control as the previous strategy (Hazim B Awbi, 1994).

III Stack-ventilation

For very large spaces or buildings with large heat gains a more complex system is required to increase the air flow rate from outside. The entry of fresh air into the building is at a low level and its exhaust at a high level to provide a large height to increase the effect of buoyancy or stack effect. With a good design these systems can be very effective and give more control over the air flow than the other two strategies. They require a high ceiling, minimum of four meters, to be viable and are therefore often used in buildings which have a central atrium, chimney, or elevated part (Hazim B Awbi, 1994).

5.2. Design considerations

An overview of the design influences needs to be made to design a functioning natural ventilation system. Influences on the design are the local climate, the architectural form and the usage of the building. In the following paragraphs an overview of the influences is given.
Climate

One of the primary considerations in the design of natural ventilation systems is the geographic location of the building. This will determine the seasonal variations in the external environmental parameters air temperature, solar radiation, wind humidity and outdoor air quality.

Other considerations that influence natural ventilation design is the exposure of the building regarding to wind, rain and the sun. Most meteorological data is for open country at a reference point on or from the ground. Buildings and other obstructions can distort the wind flow and adjacent buildings in particular causing shielding from the wind, rain and the sun. Therefore, meteorological data should be adjusted to take these effects into consideration (Hazim B Awbi, 1994).

Urban canyons

Traditional urban planning has try to find to control the proportions of the streets, because the basic geometry of building heights and distances between buildings regulates access to light and solar heat. Zoning laws and building regulations usually establish height to distance ratios that limit the overshadowing that buildings may cause for public spaces and other buildings. A similar geometric abstraction of urban space, the urban canyon, has been used in urban climatology, to describe the way that urban spaces create special environmental conditions (Strømann-Andersen & Sattrup, 2011).

The microclimate parameters in an urban canyon have an important impact on the energy performance of buildings as well as on the efficiency of natural and hybrid ventilation techniques. Knowledge of wind field characteristics, velocity and direction, as well as of the temperature distribution, inside street canyons are of vital importance for the sizing of openings in order to achieve the necessary airflow for cooling and air quality purposes. The link between urban density and building energy use is a complex balance between climatic factors and the urban surroundings (Strømann-Andersen & Sattrup, 2011).

Wind gradient

Natural ventilation systems are normally specified for steady air flow through the openings, however temporary effects such as wind turbulence could cause large fluctuations in the air flow through the openings. To allow for these effects will require
severe analysis and are normally not considered in great detail for ventilation system design (Hazim B Awbi, 1994).

If the wind velocity is taken from meteorological data is often measured in large open spaces and a recalculation is necessary to find the correct wind velocity. This calculation uses the boundary layer of air as a reference point. For Singapore the boundary height is around 400 meters. At this level the velocity of different terrains are equal and thus is the terrain influence neglectable at this height. The measured speed at a certain weather station is translated with a terrain factor to a velocity at the 400 meters, after it will be translated to the final reference height of the case study. This is for a rectangular building the height of the roof and given by the following formula (Heier, 2005):

\[
V_r = V_{10} \left( \frac{h_{\text{layer}}}{h_{\text{measurement}}} \right)^{\alpha_{\text{station}}} \left( \frac{h_{\text{layer}}}{h_{\text{measurement}}} \right)^{\alpha_{\text{building}}}
\]

The wind gradient for Singapore with a wind speed of 2.2 meter per second is shown in figure 5.5.

Table 5.1 Terrain exponent \( \alpha \) is depending on the terrain (Larsen, 2006)

<table>
<thead>
<tr>
<th>terrain</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open, flat terrain</td>
<td>0.17</td>
</tr>
<tr>
<td>Terrain with scattered growth</td>
<td>0.20</td>
</tr>
<tr>
<td>Suburban area</td>
<td>0.25</td>
</tr>
<tr>
<td>Urban area</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Figure 5.5 Wind profile for urban area Singapore with \( \alpha = 0.33 \) for a mean velocity of 2.2m/s in different terrains.
Very limited research has been performed regarding the influence of the urban wind characteristics on the sizing of building openings for ventilation purposes. Factors to take into account the decrease of the wind speed in the urban environment but are of simplified nature and are not proposed for dense urban environments and deep canyons.

The presence of a single obstacle

The presence of an obstacle such as a hedge, a wall or a house, can have a big impact on the surrounding disturbing the flow of downwind air by creating a wake; decrease in average velocity and increase of turbulence. The influence of the wake is on both sides of the building, two times the height on the positive side and five times on the negative side (Allard, 1998, p. 21).

![Figure 5.6 Structure of the flow around isolated obstacle. Based on image from (Allard, 1998)](image)

The presence of multiple obstacles

For dense urban areas the influence of surrounding buildings can have a mayor influence on the performance of the natural ventilation system. With wind tunnel test the wind pressure coefficients can be gained by scale modeling. These flow patterns are difficult to handle, and this area needs further research to be used in the prediction of natural ventilation models.

![Figure 5.7 flow patterns in urban canyon (Ahmad, Khare, & Chaudhry, 2005)](image)
Urban heat island effect

The urban heat island (UHI) effect is related to summer temperatures in urban areas being higher than in rural surroundings. Factors influencing the heat island effect include climate, topography, physical layout and short term weather conditions. Due to the high thermal capacity absorbed solar energy is stored in building structures.

Clouds increases the urban heat island effect, the net atmospheric radiation at ground level increases, because clouds improve the greenhouse effect. The thermal radiation emitted by the ground is associated with its surface temperature as well as with the emissivity of soil. Nevertheless, the ground surface temperature is usually higher in a city centre than in the countryside, which corresponds to the higher level of long wavelength radiation in an urban zone (Allard, 1998; Benjamin Bronsema, 2011). Measurements carried out in the USA indicate that the radiative flux measured at noon in a city centre is 20% higher than that recorded in the countryside; during the night the difference is about 10% (Allard, 1998).

In winter situation the effect helps the city to heat (There is no winter in Singapore). Normal expectations for dense city centres is a raise of 2°C, but in some cities values of 6°C to 7°C (London) and 8°C (Sao Paulo) are measured. Although not sure what the context of these measurements were (Benjamin Bronsema, 2011).

<p>| Table 5.2 The statistical data of five regions to detect UHI. (Wong &amp; Yu, 2005) |
|-----------------|-----------|-------|-------|----------|-----------------|----------|</p>
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Standard deviation</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>West region</td>
<td>22</td>
<td>27.01</td>
<td>27,52</td>
<td>25,56</td>
<td>0,58</td>
</tr>
<tr>
<td>Central region</td>
<td>56</td>
<td>27,64</td>
<td>28,31</td>
<td>25,95</td>
<td>0,59</td>
</tr>
<tr>
<td>North region</td>
<td>17</td>
<td>26,38</td>
<td>26,73</td>
<td>25,56</td>
<td>0,39</td>
</tr>
<tr>
<td>Northeast region</td>
<td>12</td>
<td>26,84</td>
<td>27,52</td>
<td>26,34</td>
<td>0,42</td>
</tr>
<tr>
<td>East region (incl. airport)</td>
<td>24</td>
<td>27,54</td>
<td>28,31</td>
<td>27,12</td>
<td>0,41</td>
</tr>
</tbody>
</table>
Research in Singapore concludes the positive influence of green on outdoor temperature and mitigating the UHI (Wong & Yu, 2005). In the high density (including the airport) and high rise commercial area the highest temperature and mean temperature of respectively 28.3°C and 28.1°C have been measured. In the five zones that have been compared the area with the most green measured 26.7°C resulting in a UHI of 1.4°C.

**Vertical temperature gradient**

A phenomenon where not much is known about is the temperature difference related to building height in a dense city. A common sense in the mountains; each 100 meters higher is one degree colder. For high-rise buildings this could lead to less cooling energy use in the top of the building. The cause of lower temperatures in the mountains is due to the lower atmospheric pressure. The higher you get, the less “air” is available. Talking about kilometres in altitude, this can be of significant influence.

![Figure 5.9 Burj Khalifa Tower, Dubai](image)

**Architectural height:** 828m  
**Occupied height:** 584.5m

![Figure 5.10 Torre de Cristal, Madrid](image)

**Architectural height:** 249m  
**Occupied height:** 210.6m

![Figure 5.11 Torre Titanium, Santiago de Chile](image)

**Architectural height:** 195m  
**Occupied height:** 184m

*Images and data from skyscrapercenter.com*

In city centres though, the physics, with heat columns and the accumulation of heat would suggest the opposite effect, colder at the bottom and warmer in the top. Enlarged by the stack pressure, heat generated by the occupants will add up to a higher temperature in the top of the building cause of the characteristics of air, warm air is lighter.

In contrary states the website of the tallest building in the world: “During the hot summer months or in the cool winters, the temperature at the top of Burj Khalifa is six degrees
cooler than at ground level”("story 98: Cooling Heights,"). This would lead to more energy efficient usage of buildings if they are taller.

Another example of temperature difference is the Torre Cristal in Madrid, in a media notification they stated: “there is more than ten degrees temperature difference between the ground floor and the highest point.” These ten degrees are not defined negative or positive, but the fact that there will be a difference in outdoor temperature on higher altitudes in city centres is unneglectable.

In a small experiment of 5 days I have measured the temperature gradient in Santiago de Chile on an existing tall office building. The Titanium office building is the second tallest office building in Chile with a height of almost 200 meters. Measurements were done from the afternoon of Wednesday the 12th till the early afternoon on Monday the 17th of August, in wintertime. Results are shown in figure 5.7.

The measurements show a small temperature difference whereas the top level temperature has high peaks in the afternoon up to 20 degrees. The ground floor temperature continues with small inclination towards a peak temperature of 13 degrees at four in the afternoon. In the mornings the ground floor temperature is slightly warmer, one to two degrees more.

![Figure 5.12 Results of temperature measurements in Santiago de Chile between top level and ground floor.](image)

The climate in Chile is completely different to that in Singapore. Measurements have been done in winter, not in comparable summer temperatures. Therefore these results are unusable for Singapore. Remaining with the unknown influence of the temperature
gradient in dense cities and further research on this topic is necessary to fully understand of the impact of natural ventilation on tall office buildings in urban context.

**Building design**

The form and height of the building have major influences on any natural ventilation strategy that is considered by a designer. Traditionally, high-rise buildings have not been considered for natural ventilation apart from a few exceptions. This is due to the large buoyancy pressures between low-level and high-level openings and as the greater wind effect on the high-level openings. If natural ventilation is considered for high-rise buildings, refined control for the ventilation openings is essential for the systems to function effectively. Other considerations such as thermal mass and building materials can have an influence on the performance of a natural ventilation system, particularly if this is integrated with a night cooling system (Hazim B Awbi, 1994).

**Building shape**

Aerodynamic behaviour is important for architectural and energy saving potential. The shape of the building defines the structural design as wind resistance practice a force on the building structure. This force is from vibration and drag on the building envelope (Vongsingha, 2015).

Figure 5.3 shows the difference in drag coefficient for different building contours tested in a wind tunnel. Even though the frontal areas of these objects have the same size, the drag coefficient are different, caused by the different shapes. The long shaped airfoil gives the lowest drag because the tail guides the airflow with a long surface and leaves only a small separation area at the back, creating a more laminar airflow. This relation is as well showed in figure 5.4, pressure differences decrease when the length of the building increases. A conflict is created in building design where optimizing the structural efficiency, thus reducing the pressure differences, and the use of natural ventilation
strategy where the pressure difference is necessary to create an airflow, have contrary desires.

![Building contour effects on drag](image1.png)  ![External pressure coefficient](image2.png)

**Figure 5.14 Building contour effects on drag**  **Figure 5.15 External pressure coefficient**

For extreme tall buildings the wind pressure can be of great influence on the structural design. Although new innovative materials and structural concepts are stronger and better resist against the external forces, there should still be an optimization in structural design, minimizing the amount of needed materials and energy.

Sustainable high-rise buildings optimize the use of these natural resources without burdening the structural design by adjusting the shape in a smart way. This tasks get more important as building trends are higher and higher. Solutions to reduce the wind force on the structure have been done. Taipei 101 in Taiwan was at his time the tallest building ever build and can withstand enormous wind loads by a simple change in the floor plan. Wind is cut by external saw tooth profile.

**Table 5.3 Overview of references where wind is integrated in the design.**

<table>
<thead>
<tr>
<th>Building design</th>
<th>Gherkin tower, London, UK</th>
<th>Pearl river tower, Guangzhou, China</th>
<th>Taipei 101, Taipei, Taiwan</th>
<th>Incheon 151 tower, Songdo, South Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Gherkin Tower" /></td>
<td><img src="image4.png" alt="Pearl River Tower" /></td>
<td><img src="image5.png" alt="Taipei 101" /></td>
<td><img src="image6.png" alt="Incheon 151 Tower" /></td>
<td></td>
</tr>
</tbody>
</table>
In China, the recent build Pearl tower reduces the wind pressure coefficients and its drag by openings in the façade that are complete open. In these wind tunnels wind generators generate energy using the deflection of wind. In London the Gherkin uses the deflection to strategically placed operable windows to enhance natural ventilation. If this actually reduces the force of the wind is the not sure, but it uses the wind in its design and operation.

The design of the Incheon 151 tower in South Korea shows how impressive building shape can be on the amount of wind load reduction. By splitting the building and slots in the corners it can reduce 60% of its moment at the base of the tower (Irwin, 2010).

### Shape and layout

Different building ratio based on different climatic zones influence the amount of maximum solar shading or solar gain respectively. Each climatic zone has its own optimum aspect ratio. The ratio for a building in cool climate zone should be 1:1, in temperate climate zone should be 1:1.6, in sub-tropical climate zone should be 1:2, and for a tropical climate zone 1:3. Looking at the aspect ratio, it can be mentioned that lower latitudes require an elongated form, in order to minimize exposure on the east and west sides. The form evolves gradually into 1:1 ratio, as a cylindrical or square form, which able utilize solar gain as much as possible (Yeang, 1997).
The location of the elevator core, vertical circulation and service ducts in the configuring of the skyscraper’s built form can contribute to its low energy performance by serving as a thermal buffer between the inside of the internal spaces with the external environment (Yeang, 1997).

**Segmentation**

Spaces or rooms can be considered as isolated (in terms of air flow) from other parts of the building. Openings to other parts of the building are small in relation to openings in the external envelope. When the spaces in a building are connected by large internal openings, they effectively form a single-cell, with the flow through an opening dependent on the flow through the other openings, such spaces are relatively common in naturally ventilated buildings, partly because of the desire to minimize internal resistance to flow and partly to enhance internal mixing. An advantage of this strategy is that wind and buoyancy will act together. Where the outlet is in a low wind pressure region and internal temperature is higher than the external. The same effect can be obtained by means of a stack chimney.

The main problem with applying vertical connecting space in tall buildings are the high pressure differences that can be generated by buoyancy due to the large height difference. Since the building act as a single space, the overall height is the determinant of the buoyancy force. For a single space of 180-meter-high the pressure difference across the envelope could be up to 140 pascal. Such pressures could cause problems in opening doors and windows (the force on a 1.5 m² door would be 210 N) (Etheridge & Ford, 2008).

The Commerzbank in Frankfurt demonstrates that with segments it can prevent temperature differences for acting over the full height of the building. The risk associated with the large buoyancy pressure difference at the top and bottom of the atrium is reduced. As well segmentation minimizes the risk of receiving significantly warmer air at top floors than those at the bottom.

A floor-by-floor basis natural ventilation system as demonstrated by the Menara UMNO can eliminate the above concern as well, but sufficient flow rates may not be delivered when the external weather conditions are not viable (e.g. under low wind speed). Leaving the office vulnerable for the moments outdoor conditions don’t allow natural ventilation and offices have to get back to old habits.
Furthermore, with the presence of wind, the cold draught occurred in the bottom floor should be taken into consideration. One concern is in terms of sizing of inlet and outlet. The pressure difference due to the wind forces would be determined by the wind pressure coefficient at the location of the inlet and outlet. By the use of segmentation, the complexity associated with sizing the openings of the spaces connected to the atrium is reduced accordingly. Consequently, segmentation allows for the design of each segment in isolation. That is, although the Torre Cube in Mexico is only 16 stories in height, the potential typology of super tall buildings can be derived from this building configuration as well.

The full benefit of the segmentation concept may be questioned. The segmentation can prevent the temperature differences from acting over the full height of the building. Consequently, the potential risks associated with the greater magnitudes of pressure difference in the bottom and top floors can be avoided. It is supposed that the concept of the ‘open wind floor’ may be regarded as an alternative for building segmentation (Liu et al., 2012).

Building occupancy and loads

The purpose of ventilating a building is to provide clean outdoor air to the occupants and to remove excessive heat from inside the building. Ventilation loads of a building are both thermal and polluted. Thermal loads are due to heat loss or gain by conduction through the fabric, solar gain, internal gain due to occupancy, lighting, equipment etc. A good ventilation system must be effective in dealing with thermal loads and controlling indoor pollutants to be of minimal values.

In this thesis the focus is mainly on office workstations related occupation. With an average heat generation of 75W, a personal computer 100W and lights and small adapters accounting for 25W, the heat load per worker is approximately 200W. Printers,
coffee and lunchrooms are separated from the work floor. Further reduction of the heat load needs to be more task specific, more or less light, graphic designers use computers with a higher heat production than a lawyer or simple accountant.

Table 5.4 Heat load for a normal office worker.

<table>
<thead>
<tr>
<th>Object</th>
<th>Heat production (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Person</td>
<td>100</td>
</tr>
<tr>
<td>Computer</td>
<td>75</td>
</tr>
<tr>
<td>Lighting and adapters</td>
<td>25</td>
</tr>
</tbody>
</table>

Natural ventilation and Air Distribution Systems

Mechanical Ventilation and Air Distribution Systems

Displacement and mixed flow air distribution within buildings are quite different and it is helpful for the building owner / designer to be aware of the fundamental effects they have on comfort, capital costs, and running costs of their building.

Mixed flow ventilation

Mixed flow distribution is the traditional method of supplying air to ventilated spaces. Cool air is blown in through the ceiling or wall to provide an even temperature and contaminant level through the space.

Mixed flow ventilation is driven by the inertia of the supply air. The volume of the air supplied for mixed flow ventilation is calculated proportionally to the supply air and room air temperature (Hazim Bashir Awbi, 2015; Hardy, 2015).

Figure 5.18 mixed flow ventilation strategy. Air supply and extraction via wall or ceiling.
Displacement ventilation

Displacement ventilation relies on the natural buoyancy forces of air to drive air motion. A displacement ventilation system supplies conditioned cool air from an air handling unit through a low induction diffuser. The cool air spreads through the floor and then heat sources lift the air up and the air passes through the occupied zone and is exhausted at high level.

Vertical temperature gradient naturally occurs between the floor and ceiling. The volume of air supply to a room is height dependent because of this gradient and the air volume supplied for displacement ventilation is proportional to the supply air and exhaust air temperatures.

With displacement ventilation, the flow of air is maintained by convective forces, which also have the effect of the concentration of pollutants rising from floor to ceiling. Research has indicated that there is less likelihood of complaints due to draughts using displacement ventilation and the air is likely to be cleaner as contaminants are removed from the occupied zone. In the comparison of the applications of mixed flow and displacement ventilation summarised below these apparent advantages are not considered (Hazim Bashir Awbi, 2015; Hardy, 2015).

Façade design

The building façade acts as a skin that wraps around the building and affects the internal environment as it interacts with the external one. A façade may satisfy the design and functional requirements (like aesthetics and structure), but once the occupants enter the building they will be concerned with the façade, materials, its colour or form and is more concerned with physical and physiological issues, thermal comfort, acoustic comfort, visual comfort and air quality (Ogwezi et al., 2012).
Mechanical systems have traditionally been used to satisfy these comfort criteria. A well-functioning façade design should reduce the demand of these systems and therefore be more efficient. Optimising a façade for energy reduction should implement each of the physiological issues as efficiently as possible. In optimizing these issues there are several conflicts. A conflict exists where a facade system may react on one issue but generating another one in that process. For example, maximising daylight by increasing the glazing ratio on a building can reduce energy loads for artificial lighting but at the same time increase the potential for solar gain which will not always be desirable. A number of conflicts can be identified:

- Shading – View
- Shading – Daylighting
- Natural ventilation – Shading
- Natural ventilation – Temperature control (warm or cold weather)
- Natural ventilation – Humidity control (warm climates)
- Natural ventilation – Acoustic comfort

Shading is generally used to reduce the heating loads in buildings due to solar gains and to reduce glare. The shading system can obstruct the outside view and also reduce the amount of daylight entering the building. When daylight is limited, the only option is to increase the use of artificial lighting, thereby making use of extra energy for lighting when the original aim was to reduce energy use altogether. This occurs in any region where there are cooling loads for all or some part of the year.

Direct sun in the workplace is almost always a comfort problem. Uncomfortable occupants will be less productive, close their window coverings, bring in energy-using portable fans, and reduce thermostat setting if possible (O’Connor et al., 1997). Good shading means occupants will have minimal complaints. Shading reduces glare. Exterior elements partially shield occupants’ view of the bright sky. Screens, glazing treatments, and shades reduce the brightness of the window. Exterior elements and venetian blinds reduce contrast by sending some light deeper into the space (improving distribution).

The need for natural ventilation clashes with other significant building issues: shading devices can obstruct the flow of air in and around a building and thereby reduce the effectiveness of a natural ventilation strategy. The free flow of air in and out of the building makes it much harder to keep indoor temperatures close to the comfort temperature.

Figure 5.20 Overview of different façade functions and conflicts by Knaack (Klein, 2013)
Openings

To collect a breeze from outside window design is more important than orientation. Wind doesn’t blow through a building; it is sucked towards areas of lower air pressure. To get a better flow larger openings on the leeward (low pressure) side and smaller openings on the windward (high pressure) side should be used. Openings near the center of the high pressure zone are more effective because pressure is highest near the center of the windward wall and diminishes toward the edges as the wind finds other ways to move around the building. Maximum benefits of cooling winds are provided by multiple flow paths and minimizing potential barriers, in this case if one opening is blocked a separate opening can still provide natural ventilation. Single spaces with less interior openings are ideal in warmer climates (B. Givoni, 1994). Any obstructions, this may be external (overhangs, finds, roller shades, etc.) or internal (curtains, shades, etc.), may represent a serious obstacle for the airflow decreasing the volume and velocity of the natural ventilation.

Wing wall

Outdoor fixed shading devices, such as vertical fins or horizontal slabs, may even be quite useful in creating larger pressure differences on the outer envelope of the building thus increasing the natural ventilation potential (Allard, 1998).

Experiments indicate that wing walls can promote natural ventilation by increasing the air change per hour and the mean indoor air speed relative to wind speed at various wind speeds and wind directions. In which the wind in an angle of 45 degrees to the wing benefits the most based on CFD analysis (Mak, Niu, Lee, & Chan, 2007).

Windows

Orientation to the breeze direction is less important than the actual design of windows and openings. There are different types of windows; and each type depends of the kind of building or the use that will be needed of the window. These types are: Fixed, Single Hung, Double Hung, Horizontal Sliding, Casement, Awning, Hopper, Tilt & Turn, among others.

- **FIXED** Cannot be opened and only purpose is for view and light to enter.
- **HORIZONTAL SLIDING** Windows move on a rail horizontally within the frame.
- **CASEMENT** A window with is hinged on the side of the window frame. It swings in or out like a door. If the hinge is at the top the window is called **AWNING**. On the bottom it is a **HOPPER** and in the center **PIVOT**.
- **TILT & TURN**: It has multiple options of opening directions. Based on casement window. Can tilt inwards at the top or open inwards from hinges at the sides.

![Different window types and breeze effect](acevedoinc.com/types/)

Not all windows have the same practicality. Window operation requires space indoors or outdoors and can generate inconvenient airflows for other occupants. Standard casement windows can deflect breezes from varying angles. Whereas the louvres or centre pivot windows have the less surface area reduction.

**Natural daylight**

Daylight has a variety in intensity which gives it an additional challenge for the building environment. To create healthy and comfortable offices light needs to be taken into account in the design. Research reveals that serious problems may occur if there is an uncomfortable level of glare (IEA, 2010; Osterhaus, 2005).

**Glare**

There are two types of glare: disability glare and discomfort glare. Disability glare is the effect of light in the eye whereby visibility and visual performance are reduced. Discomfort glare is glare that produces discomfort. It does not necessarily interfere with visual performance or visibility.
Glare from windows usually arises when direct sunlight enters the room and shines into the eyes of occupants or via reflections from visual tasks (computer screen) and surrounding surfaces. Alternatively, it may result from high window luminance, which is usually caused by sunlight reflections off exterior surfaces, for example the glazed facade of a building in the direct environment, or by a view of the sky. However, care needs to be taken to control the glaring effects of high luminance associated with the view of the sky. On the other hand, discomfort glare from daylight appears to be tolerated to a much higher degree than predicted by available assessment methods if there is a pleasant view from the window causing the glare.

These observations suggest that daylighting design has to be approached with care and a good understanding of the design parameters. Office layout relative to available exterior daylight openings and attention to the lighting of each task performed in the office are important factors in creating satisfactory working environments (Osterhaus, 2005).

**Luminance contrast**

In offices designed for frequent and prolonged computer use, windows continue to be a difficult problem to address. The increasing use of digital technologies in offices and industrial settings can create considerable challenges for workers in receiving, processing and transferring information in short periods of time. Eye movements between monitor screen, keyboard and manuscript can occur up to 30,000 times per day (Osterhaus, 2005). Often, a range of other visual tasks needs to be completed in addition to the screen-based work, and this in turn is likely to require different lighting settings. To function properly and maintain a focused image, worker’s eyes have to adapt again and again to changes in luminance, contrast and distance to a visual object.

![Conceptual model showing the relationships between the physical environment and job satisfaction. The predictor variables for satisfaction with lighting are indicated on the left side (orange rectangles) (Borisuit, 2013, p. 20)](image-url)
If visual and ergonomic conditions are inappropriate, visual tasks, especially screen-based work, may quickly lead to complaints about difficulty focusing, double images, glare, or headaches. Muscular pain may add to these complaints when workers attempt to shift their posture in order to avoid perceived discomfort, for instance, reflections of a light source in the display terminal screen (Osterhaus, 2005). Figure 5.23 shows the relation between lighting satisfaction and thermal comfort, indicating that the negative effects of glare can affect the occupant’s thermal comfort evaluation, and thus have negative affect on the natural ventilation potential.

### Luminance ratios

The occurrence of glare depends not only on absolute luminance values, but also on relative luminance values and contrast, usually expressed by luminance ratios. Osterhaus identified three zones in the field of view of an occupant. The central zone, where the visual task takes place. The adjacent zone, the zone delimited by a cone of 60, and the non-adjacent zone, delimited by a wider cone of 120 degrees. Characterized by the ratios of 1:3:10 (Carlucci, 2015). The IENSNA uses the same ratios, only adding the ratio of 1:40, a contrast anywhere in the field.

### Table 5.5 IENSNA recommended luminance ratio limits (Zelenay, 2011)

<table>
<thead>
<tr>
<th>Part of view</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between paper task and adjacent VDT screen</td>
<td>3:1</td>
<td>1:3</td>
<td>200 cd/m² (monitor)</td>
</tr>
<tr>
<td>Between task and adjacent dark surroundings</td>
<td>3:1</td>
<td>1:3</td>
<td>600 cd/m²</td>
</tr>
<tr>
<td>Between task and remote (nonadjacent surfaces)</td>
<td>10:1</td>
<td>1:10</td>
<td>2000 cd/m²</td>
</tr>
<tr>
<td>Between points anywhere in the field of view</td>
<td>40:1</td>
<td>1:40</td>
<td>8000 cd/m²</td>
</tr>
</tbody>
</table>

### Computer screens

Average screen luminance for negative-contrast screens (screens with black characters on a white background) for newer VDTs with liquid crystal displays (LCDs) are close to 200 cd/m² (Zelenay, 2011). Based on this monitor luminance and a maximum luminance ratio of 1:10 for the binocular field of vision, the maximum desirable luminance of the window would be 2000 cd/m².

### Relaxation

Relative brightness uniformity is generally desirable for physiological reasons, especially for adequate visual performance in office type settings, absolute uniformity from a psychological standpoint is not desirable as it can result in a lack of focus. Small areas exceeding the luminance ratios limits recommended by IESNA are “desirable for visual
interest and distant eye focus for periodic relaxation throughout the day” (Zelenay, 2011, p. 15).

5.3. Design Calculations

Designing natural ventilation systems is a more abstract study. With certain amount of data the flow can be calculated, and with the result the optimization process starts. The design process is an abstraction of the reality and can be seen as a tube, with an air inlet and an air outlet. Obstacles in the tube, as discussed in the paragraph 4.3., can be seen as factors determining the flow. Air as a fluid, like water, although with different characteristics, the fluid dynamics can be applied to find natural ventilation solutions. The first paragraph is about the basics in fluid dynamics. Equations in following chapters can be derived from these principles.

Bernoulli equation

The Bernoulli equation is the result of the three simplifications of the Navier-Stokes equations assuming an inviscid fluid \((Re>1)\) (Allard, 1998, p. 35):

\[
\frac{1}{2} \rho v^2 + \frac{P_S}{P_t} + \rho gh = \text{constant}
\]

The equation consists of three parts, similar to the Navier Stokes equations. This means, if there is no influence from outside nor energy loss velocity increases, the static pressure \(P_S\) has to decrease. This equation can be completed summing the effects of a turbo machine (like a fan) (Ortega, 2011). The formula is then:

\[
\frac{1}{2} \rho v^2 + P_S + \rho gh + \Delta P_{fan} = P_t
\]

Mass flow rate

Consider flow through the pipe-work shown in Figure 1.3, in which the fluid occupies the whole cross section of the pipe. A mass balance can be written for the fixed section between planes 1 and 2, which are normal to the axis of the pipe. The mass flow rate across plane 1 into the section \(\rho_1Q_1\) is equal to and the mass flow rate across plane 2 out of the section is equal to \(\rho_2Q_2\), where \(\rho\) is the density of the fluid and \(Q\) the volumetric flow rate. The mass balance can be written as (Holland & Bragg, 1995):
\[ \rho_1 Q_1 = \rho_2 Q_2 + \frac{\partial}{\partial t} (\rho_{av} v) \]

**Mass flow rate in = mass flow rate out + rate of accumulation within the pipe section**

![Flow through a pipe of changing diameter (Holland & Bragg, 1995).](image)

The wind and stack pressures will be equal to the sum of the velocity pressure at the inlet and outlet and the pressure losses in the flow path.

**Wind pressure**

For calculating the wind flow for wind based ventilation (single sided or cross-ventilation), the static pressure in front of the façade needs to be positive, resulting in a flow from positive to negative. Therefore we need to know the wind pressure at the surface of a building or a ventilation opening and is given by the following equation (Hazim B Awbi, 1994).

\[ P_w = \frac{1}{2} \rho v_r^2 \cdot C_p \]

Where part of the Bernoulli equation, the kinetic energy, is multiplied by the wind pressure coefficient. \( C_p \) is a function of wind direction, position on the building surface and site exposure (Hazim B Awbi, 1994). The reference wind is derived from the formula of the wind gradient in equation 9.

**Stack pressure**

Buoyancy is the force, along with the gravity, involved in the movement to upper positions of an object or fluid with less density than the fluid surrounding. In ideal gases when the temperature increases, the density decrease, thus a movement between the cold and warm zones appears. The pressure difference of the stack effect is in the following equation (Hazim B Awbi, 1994).

![Stack pressure increases with height. Height of the chimney is an important factor.](image)
\[ \Delta P_{\text{stack}} = gh\Delta \rho \]

\[ \Delta P_{\text{stack}} = \rho g L \frac{\Delta T}{T_a} \]

The influence of the height is more than linear. The exact relation depends on the resistance of the chimney. In theory the higher the chimney the more solar radiation will be added resulting in a higher \( T \) at the output.

A chimney is device usually used to remove the hot flue, gas or smoke to the atmosphere. It uses the stack effect to induce the movement. In buildings, the chimney also is used in natural ventilation, taking advantage of the differences of temperature between in-outside the building.

**Pressure losses**

In every duct system there are pressure losses due to the circulation of fluids inside the duct (primary pressure losses) and caused by additional components as a valve, contractions or inlets (secondary pressure losses). These pressure losses can be incorporated in the Bernoulli equation (Ortega, 2011):

\[ \frac{1}{2} \rho v^2 + P_s + \rho g L + \Delta P_{\text{fan}} = P_t + \frac{1}{2} \rho v_m^2 \cdot \sum K_{\text{drop}} \]

Where \( v_m \) is the mean air speed in the duct and \( \sum K_{\text{drop}} \) signifies the sum of the primary and the secondary pressure losses in the system.

**Primary pressure loses**

Pressure loss (\( \Delta p \)) as result of friction in a constant rectangular channel is calculated with the formula (Benjamin Bronsema, 2011):

\[ \Delta p = \lambda \frac{L}{D_h} 0.5 \rho v_m^2 \]

With \( L \), the length of the chimney and \( \lambda \) the friction factor. The hydraulic diameter (\( D_h \)) of the rectangular duct is defined as (Ben Bronsema, 2011):

\[ D_h = \frac{2w+h}{w+h} \]
Where the \( w \) and \( h \) are the sections of the duct.

The friction factor \( \lambda \), is calculated via the empirical formula of Colebrook-White (Benjamin Bronsema, 2011):

\[
[\text{EQ 19.}] \quad \frac{1}{\sqrt{\lambda}} = -2 \log \left( \frac{e}{3.72D_h} + \frac{5.74}{Re^{0.301}} \right)
\]

Where the material roughness \( (\varepsilon) \) and the Reynolds number influence the friction in the chimney. Friction factor is derived via substitution of the formula of Colebrook-White:

\[
[\text{EQ 20.}] \quad \lambda = \left( \frac{1}{-2 \log \left( \frac{e}{3.72D_h} + \frac{5.74}{Re^{0.301}} \right)} \right)^2
\]

Where the Reynolds number is defined by the formula (Ben Bronsema, 2011; Ortega, 2011):

\[
[\text{EQ 21.}] \quad Re = \frac{v_m D_h \rho}{\text{Viscosity}}
\]

Where, \( v_m \) is the volumetric average velocity of the fluid, \( D_h \) is the internal diameter of the pipe, and \( \rho \) and \( V \) are the fluid’s density and viscosity. Showing the relation of friction in relation to the velocity of the fluid in the chimney.

Reynolds number

The Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. If the number is high (\( Re > 1 \)) the viscous forces can be neglected and as well it defines if the flow is laminar or turbulent (Ortega, 2011):

- Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion (\( Re < 2300 \)).
- Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities (\( Re > 4000 \)).

Wall roughness

The roughness of the wall is defined by the roughness factor \( \varepsilon \). The values for wall roughness for solar induced systems are higher than then the values for the materials...
itself. Type of connections, status of the materials etc. therefore values for solar chimneys are unknown. There is a positive correlation between wall roughness and the prestige of the solar chimney. The following mechanisms play part in this (Benjamin Bronsema, 2011):

- The turbulent heat transfer convection of the walls rises with a higher resistance in the chimney. Higher viscosity and thus higher heat transfer.
- The resistance factor λ which part of the determination of the primary pressure losses of the airflow will rise when the roughness factor increases. It is tempering to increase the heat transfer to increase the prestige of the chimney by increasing the wall roughness.
- The higher air temperature that is realized by the increasing the friction results in a higher stack effect. Which is partly needed to overcome the higher pressure losses.

Table 5.5 shows the roughness factor for different materials.

Table 5.5 Roughness coefficients for different materials (ToolBox), *(Ben Bronsema, 2011, p. 65).

<table>
<thead>
<tr>
<th>Surface material</th>
<th>Roughness coefficient [MM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper, Lead, Brass, Aluminum (new)</td>
<td>0.001 - 0.002</td>
</tr>
<tr>
<td>PVC and Plastic Pipes</td>
<td>0.0015 - 0.007</td>
</tr>
<tr>
<td>Glas*</td>
<td>0.0015</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.015</td>
</tr>
<tr>
<td>Steel commercial pipe</td>
<td>0.045 - 0.09</td>
</tr>
<tr>
<td>Stretched steel</td>
<td>0.015</td>
</tr>
<tr>
<td>Weld steel</td>
<td>0.045</td>
</tr>
<tr>
<td>Galvanized steel</td>
<td>0.15</td>
</tr>
<tr>
<td>Rusted steel (corrosion)</td>
<td>0.15 - 4</td>
</tr>
<tr>
<td>New cast iron</td>
<td>0.25 - 0.8</td>
</tr>
<tr>
<td>Absorption plate*</td>
<td>0.07</td>
</tr>
<tr>
<td>Worn cast iron</td>
<td>0.8 - 1.5</td>
</tr>
<tr>
<td>Rusty cast iron</td>
<td>1.5 - 2.5</td>
</tr>
<tr>
<td>Sheet or asphaltated cast iron</td>
<td>0.01 - 0.015</td>
</tr>
<tr>
<td>Smoothed cement</td>
<td>0.3</td>
</tr>
<tr>
<td>Ordinary concrete</td>
<td>0.3 - 1</td>
</tr>
<tr>
<td>Coarse concrete</td>
<td>0.3 - 5</td>
</tr>
<tr>
<td>Well planed wood</td>
<td>0.18 - 0.9</td>
</tr>
<tr>
<td>Ordinary wood</td>
<td>5</td>
</tr>
</tbody>
</table>

Viscosity

For flows with high Re, the effect of the viscosity is neglected. Though areas close to walls the viscosity will affect the prestige of the chimney (Ortega, 2011). This area is the
boundary layer and its study is very important to understand the behaviour of the solar chimney.

![Figure 5.26 Boundary layer on flat plane (Ortega, 2011)](image)

**Secondary pressure loses**

For each opening there is certain resistance and thus pressure loss. For normal openings the value is between 0.0-1.0 and is depending on the diameter and the profile’s form.

\[
\Delta p = \left( K \left( \frac{A}{A_i} \right) + K_o \left( \frac{A}{A_o} \right) + K \left( \frac{A}{A_n} \right) \right) \times \rho v_m^2
\]

With \( K \) as the pressure loss coefficients; \( A \) is the cross-sectional area of the ventilation channel; \( A_i \) and \( A_o \) are the areas of the inlet and outlet respectively, but can be expand by multiple \( A_n \) components. These secondary components of the system have their own pressure loss coefficient \( C_{Dn} \), and in the most of the cases can be calculated with charts. Secondary pressure losses can be due to inlet, outlet, nozzles and valves. Each component has a constant coefficient of pressure loss (Ortega, 2011).

**Discharge coefficient**

Each opening has a certain resistance and should be multiplied by a discharge coefficient by its own.
Flow characteristics of openings

The volume flow rate through an opening is given by Bernoulli’s equation (Hazim B Awbi, 1994):

\[ Q = C_d A_e \sqrt{\frac{2\Delta P}{\rho}} \]

Or via the temperature differences (Ham, 2013):

\[ Q = C_d A_e \sqrt{2gh \frac{\Delta T}{T_a}} \]

Delta T is retrieved as a formula of the solar radiation (Ham, 2013),

\[ \Delta T = \frac{\frac{\Delta \text{Heat}}{2} - \frac{T_A^3}{(2gh)^2}}{\frac{\Delta \text{Heat}^2}{2} + \frac{\Delta \text{Heat}^2}{2} + \frac{T_A^3}{h^2}} = 0.0279 * \left( \frac{\Delta \text{Heat}^2}{h^2} \right)^{\frac{1}{2}} \]

\[ \Delta \text{Heat} = \text{sol}ar \text{ rad}iation \ W \]

\[ \text{Heat}_\text{spread} = \text{Heat release in duct. Equal release is 2, full mix Tin} = T_{gem} \]

Where \( A_e \) is the equivalent for the opening area and \( C_d \) is the discharge coefficient due to secondary pressure losses. \( \Delta P \) is the pressure difference between the openings, \( \rho \) is the density of the air. For parallel openings:

\[ \frac{1}{A_e^2} = \frac{1}{(A_1 C_{d1})^2} + \frac{1}{(A_2 C_{d2})^2} \]

Figure 5.28 parallel opening
For more than one opening:

\[
\frac{1}{Ae^2} = \frac{1}{(A_1 + C_{d1})^2} + \frac{1}{(A_2 + C_{d2})^2} + \frac{1}{(A_n + C_{dn})^2}
\]

And for openings in series

\[
A_{e(\text{series})} = A_1 \cdot C_{d1} + A_2 \cdot C_{d2} + A_n \cdot C_{dn}
\]

5.4. Wind and solar induced ventilation

Solar induced ventilation

Trombe Walls and solar chimneys are passive building elements which rely on solar-induced buoyancy-driven convection. In contrast to fan-driven (forced) convection, buoyancy-driven (natural) convection components are more difficult to analyse and it is more difficult to predict their performance, not least because mass flow depends on the heat input and also on the geometry of the system, and therefore it is not easily controlled (Burek & Habeb, 2007). Buoyancy-driven convection from a single vertical plate has been studied extensively. In Trombe Walls and solar chimneys the flow is constrained within a vertical channel characterized by heat convection coefficients, changing radiation flux of the moving sun and the dynamics of turbulent airflows which are hard to predict (Benjamin Bronsma, 2011, p. 26). The flow profile in solar induced ventilation systems is less constant due to the following reasons:

- Incoming radiation causes temperatures difference on the heat absorber, with inherent velocities.
- The wall roughness of the chimney is probably bigger in comparison to normal metal ventilation ducts. It is therefore hard to predict the flow.
- Probably the temperature differences in the chimney between the walls will cause turbulence.

Solar chimney

A solar chimney uses the solar radiation to increase the temperature inside generating the stack effect to move the air. Therefore built and coated in some dark or black material to minimize the amount of sunlight that is reflected off of the chimney, absorbing more of the heat. Ensuring more of the heat is transferred to the air inside the building. Two additional vents, one at the top of the chimney, and a second at the opposite end of the
building to allow air for ventilation. Solar radiation hits the side of the chimney, the column of air inside the chimney is heated and by opening the top vent (so that air is not trapped) is pulled up and out of the chimney, pulling new air in from the outside and creating a sort of "draft" that provides cool, fresh air into the building.

**Chimney types**

There is not a single design for solar chimneys. The geographic location, the height of the building, the solar collector and the materials are of influence on the chimney. Nowadays, the most widely used is that one that replaces part of the south facade for a glazing allowing, the solar radiation, to get inside the chimney (Ortega, 2011). In general we can distinguish three different main types of solar chimneys:

*Type One: Full stack height*

The solar radiation passes through the glazing, situated in the down part of the south façade, and it is absorbed by the solar collector (in the bottom of the chimney). The solar collector is a high number of thin parallel metallic fins; the fin receives the solar radiation, increasing the temperature of the surfaces, this generates a convection plume for each fin. The distance between two fins is relative small. There is a homogenous temperature inside. When the height of the chimney is bigger (3m) than “h”, it can be assumed that the height of the chimney and the height of the stack effect it is the same (Ortega, 2011).

*Type Two: Cold climate*

This type of chimney is installed in the Tånga School in Falkenberg Sweden. The chimney is designed for cold climates (higher latitudes), that’s why just a part of the south facade is a glass to minimize the heat loss trough the chimney. This chimney also uses the stack effect of the building to improve natural ventilation.
The radiation passes the window and is absorbed by the solar collector, but in this case it is the front wall, which is painted in black to improve the absorption of radiation. In this case the height of the chimney and the height of the stack there are not the same; as an approximation, the beginning of stack effect’s height can be calculated as the point where the thermal boundary layer touches the south wall (Ortega, 2011).

Type Three: tropical climate.

This kind of solar chimney is for warmer and tropical climates. The design is simple; the south wall is made of glass. It allows the radiation to the solar collector, which is the front wall. Like type Two, the height of the stack effect differs from the height of the chimney; and is defined by the thermal boundary layer.

Trombe wall

Cooling a space using a solar chimney is slightly different than cooling using a Trombe wall. The biggest difference is that the outlet of the air is on the side, the wall, instead of the top. This makes it a better application for high-rise facades. The Trombe wall is free heating system but can be used to ventilate a building. In this case the heat is extracted and fresh cool air is drawn into the building. Decreasing the room’s temperature and thus cooling the building. Table 5.1 shows the cooling and heating options.

Table 5.1 Trombe wall functionalities.

<table>
<thead>
<tr>
<th>Daytime heating</th>
<th>Night time heating</th>
<th>Daytime cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Daytime heating" /></td>
<td><img src="image2" alt="Night time heating" /></td>
<td><img src="image3" alt="Daytime cooling" /></td>
</tr>
</tbody>
</table>
Double skin façade

The Double Skin Façade system is based on the Trombe wall. The system becomes more interesting with explorations for transparent and glass architecture and as environmentally “responsible” design strategy. Early modern architects such as Le Corbusier, with his “mur-neutralisant”, and Alvar Aalto, in the window design of the Paimio Sanatorium, explored this new building technology. Essentially the double skin façade is a pair of glass “skins” separated by an air corridor. In general three types of double skin façade systems are identified, buffer, extract and twin face systems. A fourth non transparent is added as hybrid double skin façade (Ortega, 2011).

I. Buffer system

These façades date back some 100 years and are still used. They predate insulating glass and were invented to maintain daylight into buildings while increasing insulating and sound properties of the wall system. They use two layers of single glazing spaced 250 to 900 mm apart, sealed and allowing fresh air into the building through additional openings. Shading devices can be included in the cavity.

II. Extract Air system

These are comprised of a second single layer placed on the interior of a main façade of double-glazing. The air space between the two layers of glazing becomes part of the HVAC system. The heated “used” air between the glazing layers is extracted through the cavity with stack or with the use of fans while the outer layer of insulating glass minimizes heat-transmission loss. Fresh air is supplied by HVAC and precludes natural ventilation. The air contained within the system is used by the HVAC system. Occupants are prevented from adjusting the temperature of their individual spaces. This system is used where natural ventilation is not possible (for example in locations with high noise, wind or fumes).
III. Twin Face system

This system is distinguished from both Buffer and Extract Air systems by openings in both of the facades to allow natural ventilation. This system consists of a conventional curtain wall or thermal mass wall system inside a single glazed building skin. This outer glazing may be safety or laminated glass or insulating glass and is primarily used for protection of the air cavity contents (shading devices) from weather and to block/slow the wind in high-rise situations and allow interior openings access fresh air without the associated noise or turbulence.

The internal skin insulates the building minimizing heat loss, windows on the interior façade can be opened, while ventilation openings in the outer skin moderate temperature extremes within the façade. The use of windows can allow for night-time cooling of the interior. For sound control, the openings in the outer skin can be staggered or placed remotely from the windows on the interior façade. The RWE Tower in Germany would typify a classic Twin-Face building.

IV. Hybrid system

The hybrid system combines various aspects of the above systems and is used to classify building systems that do not “fit” into a precise category. Double skin systems that included more opaque elements, and screen elements that are used to control the amount of heat, solar gain, and ventilation in buildings. Such buildings may use a layer of screens or non-glazed materials on either the inside or outside of the primary environmental barrier. The Tjibaou Center in New Caledonia by Renzo Piano may be used to characterize this type of Hybrid system.

---

**Figure 5.34 The four double skin façade systems (Ortega, 2011)**
Efficiency of solar induced façade system

In solar systems a conversion of photothermic radiation to heat takes places (Benjamin Bronsema, 2011). Where the efficiency depends on the amount of solar radiation captured on one side, on the other side, minimum heat loss to the surrounding. For a maximum absorbance of energy the chimney needs a glass surface with high g-value and an absorber, the inside of the chimney, with a high absorbance coefficient.

Heat loss is due to conduction, convection and radiation. Conduction and convection can be limited with a high heat resistance of the glass pane and inside wall. Whereas the radiation losses are minimized with low heat emission factor (insulative). The absorber needs to have a high absorbance factor to absorb the solar radiation and a low emission factor for heat radiation so that all the energy can be transferred via convection and conduction (Benjamin Bronsema, 2011).

Transmittance of glass

For a global overview of the glass differences see table

<table>
<thead>
<tr>
<th>Nr</th>
<th>Glass type</th>
<th>G-value</th>
<th>U-value</th>
<th>Notification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clear white double glass</td>
<td>0.7</td>
<td>3.0</td>
<td>High U-value</td>
</tr>
<tr>
<td>2</td>
<td>HR++ glass</td>
<td>0.64</td>
<td>1.1</td>
<td>Low radiation entrance</td>
</tr>
<tr>
<td>3</td>
<td>Thermoclear triple</td>
<td>0.68</td>
<td>2.0</td>
<td>waste</td>
</tr>
<tr>
<td>4</td>
<td>double glass with argon</td>
<td>0.75</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Low E</td>
<td>0.7</td>
<td>1.32</td>
<td></td>
</tr>
</tbody>
</table>

- Clear white glass has a relative high U-value. High amount of heat loss will occur.
- HR++ glass has a good U-value but a relative low radiation entrance factor.
- The triple thermoclear is relatively heavy and not environmental friendly.

Interior wall

Incoming solar radiation is absorbed by the inside of the walls. As result the surface temperatures rise, and the convection flow starts. The solar radiation transmits heats via the surface to the structural elements of the chimney. An inside wall of the chimney with a high heat capacity, the trobme wall, can absorb this heat and use the stored heat in a later moment when there is less radiation. This can be ideal for night-time ventilation (Benjamin Bronsema, 2011). For offices however it is the challenge to use a high insulative wall to use the solar radiation during the daytime without thermal losses to the structure.
Average Ground Reflectance

Average Ground Reflectance is defined as the average fraction of incident radiation reflected by the ground. The respective values should be in a percentage form (e.g. 0% stands for total absorption and 100% for total reflection). The following table reports estimates of average reflectance values respecting different materials. 20% reflectance is normally used for calculations (InteLLigence, 2016).

<table>
<thead>
<tr>
<th>Ground cover</th>
<th>Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (large incidence angles)</td>
<td>7%</td>
</tr>
<tr>
<td>Coniferous forest (winter)</td>
<td>7%</td>
</tr>
<tr>
<td>Bituminous and gravel roof</td>
<td>13%</td>
</tr>
<tr>
<td>Dry bare ground</td>
<td>20%</td>
</tr>
<tr>
<td>Weathered concrete</td>
<td>22%</td>
</tr>
<tr>
<td>Green grass</td>
<td>26%</td>
</tr>
<tr>
<td>Dry grassland (Standard)</td>
<td>20–30%</td>
</tr>
<tr>
<td>Desert sand</td>
<td>40%</td>
</tr>
<tr>
<td>Light building surfaces</td>
<td>60%</td>
</tr>
</tbody>
</table>

Façade concepts

In hot humid regions the temperature may be quite high during the rains and, of course, accompanied by high humidity. In this situation ventilation is very important for comfort during the rain. Therefore, the design of the building should enable natural ventilation also during the rainy period, even when accompanied by high winds, with effective prevention of water penetration through the open window or doors.

Monsoon window

The monsoon window is designed to achieve continuous natural ventilation with a cross section that allowed for air movement at different body levels. Above the windows are ventilation grilles. These are protected from rain penetration by an overhanging floor slab with a down hanging fascia parapet. Vertical pivot windows and horizontal ventilation slots at sill height allows for ventilation at body level. These horizontal ventilation slots allow airflow into the building even if the windows are closed. The original sketch of Bawa, for the State Mortgage Building in Sri Lanka, shows operable windows below the window sill which would have allowed low level ventilation but they were not implemented because the structural beams got in the way (Kiang & Robson, 2006).
Brise Soleil

Brise Soleil, a forgotten passive sun protection method to protect against the sun. The term “Brise Soleil” refers to a rigid sun protection system, which most often consists of fixed slats or sun protection grids (urbanalyse, 2012). Attached to the outside facade in front of windows or across the whole building surface. Traditionally used in North Africa, Le Corbusier integrated it into modern architecture and constructed them as massive concrete, or from covered steel created, shelf-like protrusions, as, for example, on his buildings in Chandigarh, India.

The project of the Brise Soleil for the ministry of education and Health in Brazil divides the façade into boxes measuring 5m x 2m, with 1,3m depth, and 3 horizontal panels fixed to the sides, projecting themselves 50cm beyond the window. The louvres are developed for the mid-day sun in summer, and for a 45 degree winter sun, Strategies for dispelling the heat that formed between the sun-breaker and the interior of the building were found necessary, thus the 50 cm space between the Brise Soleil and the window. Due to the relative movement of the sun, the use of horizontal louvers is useful. Near the equator, the protection offered by overhangs is more effective and the slats can be designed in a way that avoids a significant reduction of the visual field. The luminous
fields generated by the louvers are more stable and penetrate deeper into the room, resulting in significant energy saving (Naves, Amorim, & Szabo).

Figure 5.38 slats are high positioned to optimize the view. façade, with vertical fixed lamellas and horizontal moveable dark slats.

Figure 5.39 Northwest façade, with vertical fixed lamellas and horizontal moveable dark slats.

Figure 5.40 Mechanism to rotate the horizontal slats.

5.5. Conclusion on natural ventilation

For the tropical environment of Singapore the use of prevailing wind can serve to reduce cooling energy usage. To control the humidity level, airflow control needs to be high. Controlling the exhaust is easier than the inlet as the airflow is not constant and wind comes from different directions.

To enhance the supply and the extraction of air several strategies seem to increase passive natural ventilation in the city context of Singapore:

Other wind driven ventilation types are single sided ventilation. This will be less effective due to the less pressure difference in the facades. In this case the height and the depth allow smaller offices.

Stack ventilation can be an additive on cross ventilation if openings have different heights. Even if there is no wind there can be still a small pressure difference due to the occupant’s heat generation.

In case humidity level and or the outside temperature is too high cross-ventilation is not an option as it let the air enter the office without any treatment. This will result in a less comfortable environment which will lead to lower productivity. Something that should be avoided.

Another warning for this strategy is its stapling effect of heat absorbance on its path. At each person the airflow will get warmer due to heat transfer. In this way the air will have
different temperature between one side and the other side of the office if the velocity of the airflow is not sufficient.

In free running buildings the acceptable temperatures are higher due to the self-control and relation to outside conditions. This brings on one hand a reduction in cooling load as it is not necessary to achieve same temperatures as in full HVAC controlled buildings, on the other hand it increases the amount of hours natural ventilation is acceptable.

Of the discussed natural ventilation techniques not all of them are applicable to offices in high rises. With the prevailing wind cross ventilation should be available and thus an open office is desirable. Single sided ventilation is less efficient and with the high demand it is not efficient in relation with cross ventilation. Stack effect needs a height of 4 meters and is thus less interesting as height is not always available.

Solar induced ventilation can be interesting as there is the tropical solar chimney that is relatively light and won’t use the complete façade. If used in a smart way, the chimneys can be stacked and windows can still cover large part of the façade.

**Table 5.2 passive ventilation strategies**

<table>
<thead>
<tr>
<th></th>
<th>Applicable</th>
<th>Costs</th>
<th>Energy saving</th>
<th>Operable windows</th>
<th>Combine with wind strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1) Wind</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Cross ventilation</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>b. Single sided ventilation</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>c. Stack ventilation</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>2) Solar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Solar chimney</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>b. Double facade</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>c. Trombe wall</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Based on literature, human thermal comfort and the local climate data of Singapore the amount of hours where solely NV is limited; 2557 hours within the RH limit and only 404 hours within the upper comfort range. In order to design a year round comfortable office environment the design should be supported by a HVAC system. For existing buildings there is already a centralized HVAC infrastructure to support the NV and thus easy to maintain/reuse this infrastructure. For new buildings a decentralized system may be more efficient, but this is not part of this thesis.
6. RESEARCH & DESIGN

Based on the local climate analysis, the metrological data and the literature about natural ventilation and human thermal comfort; cross ventilation in combination with a secondary passive extraction chimney will be investigated.
6.1. Research

Based on the learnings from literature, local climate and reference projects start of the design can be made. The acquired knowledge is the base for the design requirements, design limits, design boundaries and design strategies and will form the concept and finally the design. The following list are my most relevant findings for façade design in Singapore.

CHAPTER HIGH-RISE

- Bioclimatic approach
- Sun shading
- Orientation
- Core position
- Office buildings up to 300-meter high.
- Mixed mode as solution to foresee always comfort

CHAPTER CLIMATE

- Natural ventilation only passive technique
- North south Prevailing wind
- Warm
- Humid
- Clouds / low radiation
- Equal divided radiation per building orientation

CHAPTER THERMAL COMFORT

- Adaptive thermal comfort is possible to get comfortable with 30 degrees
- 10%PPD to maintain comfort
- Airflow can cool up to 2 degrees
- Humidity up to 80% ~normal higher can cause extra discomfort
- Outdoor temperatures have a discomfort heat peak between 13:00 and 16:00.

CHAPTER NATURAL VENTILATION

- Design of windows is more important than wind direction. Wind is extracted not pushed.
- Wind catchers as wind wings can guide airflow
- Urban canyon is hard to predict
- Stack ventilation for high loads higher than 4 meters
- Cross ventilation up to 15 meters of office depth
- Single sided ventilation is less effective and up to 5 meters office depth only
- Monsoon windows and Brise-Soleil are proven techniques for tropical climate
- Solar chimney or induced stack ventilation can reduce cooling load

With this information the design of energy reducing façade can be started.
6.2. Design process

For the facade design a process needs to be passed, iterating towards the final design. In this process the concept is formed by the design strategy, whereas the different components will be evaluated and combined to maximize energy efficiency of the office, and still maintain comfortable and thus doesn’t influence the working efficiency of the occupants.

Figure 6.1 Design process, from definition of the used strategy till analyse of the final product.
Stages of the design process

• **DESIGN STRATEGY**

  **DEFINE:** The problem is explained and a design strategy to approach the situation. Design process limitations and requirements for the rest of design process are composed. The valuation criteria and validation factors are summed to be taken into account during the optimizing of the design.

  **PRODUCTS:** Design goal, design requirements, validation criteria, design limitations, design strategy and design approach.

• **CONCEPT DESIGN**

  • **COMPONENTS:** Initiating design with components formed by the design strategy. Defining functions and energy saving potential.
  
  • **COMBINE:** combining of components and its energy saving potential.

  **PRODUCTS:** Concept design, components of concept design, hours HVAC saving of concept and performance of concept components.

• **OPTIMIZATION**

  **VALIDATION:** possibilities to maximize positive effects on the validation factors and saving potential. Not all factors can be of the same influence, and some are critical for the final design and should be taken in to account with care.

  **PRODUCTS:** Validation of concept design based on rating factors.

• **ANALYZE**

  **SELECTION:** select a design that is analyzed and optimized for the list of requirements the process has to be repeated for all the requirements.

  **PRODUCTS:** a smart, simple and effective design, list with incorporations and concerns.

During the design findings and new insights occur. Therefore, it is needed to update the definition and the boundaries that are required for the final design.
6.3. Definition

In the literature there are several systems that enhance passive natural ventilation but not all of them have the same efficiency or desired results if applied to the environment of Singapore. A working design requires a certain strategy which makes decisions easier during the design process.

Design goal

Comparing the façade design with the design of a high performance car, where the goal is to design a car that uses a minimum amount of fuel for a certain trip. In this practice there are several design questions that quantify the petrol usage; comfort, type of road, aerodynamics, weight, driver, etc. In the image below there are two extremes visible; extreme comfort and extreme fuel economy. What we want is to design the most comfortable car, with the less amount of fuel. In this give and take process, there has to be compromises to find the solution.

*Energy / fuel efficiency vs. comfort*

![Figure 6.2 The Ecorunner 5 from TU Delft, 3653 km/l (ecorunner.nl)](image1)

![Figure 6.3 Interior extended Rolls Royce Phantom, 0.14 km/l (1:7; autowereld.nl)](image2)

The same is for the design of an office façade in Singapore. Due to the high humidity and high temperatures, the system cannot solely rely on passive ventilation strategies. At some moment cooling/dehumidification is required, and thus the actual task is to reduce the energy usage of the system of a complete year, and not solely the amount of hours the windows can be open to enhance passive ventilation. With a mixed system, sensors should react on the conditions, indoor and outdoor, resulting in a weighted solution where there is an optimum usage of the resources. Where energy, ‘fuel’, is saved in comparison with the standard, the energy saving potential or HVAC saving hours as it will be called in the design approach.
Design requirements

EXISTING OFFICE

The design should be broad applicable. Main design is for existing building stock to have a big as possible market and thus saving potential. The design should be an addition to the existing infrastructure.

FLEXIBLE FLOOR PLAN

The two best examples for natural ventilation in offices have been transformed into HVAC buildings due to the lack of caretakers and not flexible design. This should be avoided and taken care in the design.

COMFORTABLE OFFICE

The office should be comfortable and therefore not infringe thermal comfort and in general the indoor environment. For this reason, temperature, relative humidity and window wall ratio limits will be used.

COOLING LOAD REDUCTION

The façade should reduce the cooling load. This is measured by the hours of HVAC saving. With the supposition that energy is saved by the application of natural ventilation or the support of the centralized HVAC system.

Design strategy

The design strategy is based on the local climate analyze combination with a passive design approach of the façade system.

---

**Figure 6.4 Overview design strategy with subcategories.**
Cooling load reduction

Shading

A strategy that reduces the cooling load is to block all direct radiation from the sun. By blocking the sun internal heat load can be reduced and indoor comfort is improved.

Vertical lamellae not sufficient. Not all the radiation is blocked. Combination of horizontal and vertical lamellae keeps all the sun out.

Figure 6.5 solar shading lamellas

Due to the geolocation of Singapore both horizontal as vertical lamellae are needed to fully block the sun. The implementation of these lamellae is for granted, the exact design is not incorporated in this thesis as it is more reliant on the total amount of flow and temperatures.

Table 6.1 Sun shading strategy positive and negative characteristics

<table>
<thead>
<tr>
<th>Judgement</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal lamellas</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>Influence on indoor airflow pattern</td>
</tr>
<tr>
<td>+</td>
<td>Reducing external heat load when sun is high</td>
</tr>
<tr>
<td>-</td>
<td>Daylight reflector</td>
</tr>
<tr>
<td>-</td>
<td>Visual obstruction</td>
</tr>
<tr>
<td>Vertical lamellas</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>Wind collector, as wind wing</td>
</tr>
<tr>
<td>+</td>
<td>Less glare</td>
</tr>
<tr>
<td>+</td>
<td>Reducing external heat load for low sun altitude</td>
</tr>
<tr>
<td>-</td>
<td>Visual obstruction</td>
</tr>
<tr>
<td>-</td>
<td>Due to geographic location needed on both sides</td>
</tr>
</tbody>
</table>

Adaptive thermal Comfort

Adaptive thermal comfort allows higher internal temperatures, reducing the cooling demand and thus HVAC reliance. Due to the relation between inside and outside conditions windows should be operable.
Natural ventilation

Several strategies have been discussed in the literature. Cross ventilation and stack effect will be applied in the design process.

Cross ventilation

The use of windows on opposing facades gives an airflow, if there is a pressure difference. Cross ventilation normally is related to window dimensions and gives a high capacity of ventilation rate.

<table>
<thead>
<tr>
<th>Judgement</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Use of local prevailing wind</td>
</tr>
<tr>
<td>+</td>
<td>Easy accessible</td>
</tr>
<tr>
<td>-</td>
<td>Dependent on outside conditions</td>
</tr>
<tr>
<td>-</td>
<td>Air will heat up in its path in the office</td>
</tr>
</tbody>
</table>

The north-south prevailing wind can be used to increase volume change. Where there is wind it can be applied if outside conditions, temperature and humidity are sufficient to allow open windows. A disadvantage of cross ventilation is the temperature gradient on its path. By adding heat to the flow, the temperature will rise what can be undesirable by occupants sitting on the opposite façade where the airflow is leaving the office.

Stack ventilation

A solar chimney extracts air in a controlled way and can be used in combination with cross ventilation (if this is not sufficient to remove the internal heat load). As the solar radiation in Singapore is not optimal due to clouds, pressure difference can still be generated by wind and can be exploited by its height.

<table>
<thead>
<tr>
<th>Judgement</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Pressure driven, sun and or wind</td>
</tr>
<tr>
<td>+</td>
<td>Independent of RH or rain</td>
</tr>
<tr>
<td>+</td>
<td>Functions as external solar shading</td>
</tr>
<tr>
<td>+</td>
<td>Functions as air catcher for cross ventilation</td>
</tr>
<tr>
<td>-</td>
<td>Visual obstruction</td>
</tr>
<tr>
<td>-</td>
<td>Relative costly ‘second façade’</td>
</tr>
<tr>
<td>-</td>
<td>Cloudiness Singapore</td>
</tr>
</tbody>
</table>
Mixed mode

Other strategies should be implemented aside the cross and solar induced ventilation strategies to regulate ventilation in case the outside conditions don’t allow cross-ventilation is by using a hybrid strategy where a mechanical system supports the natural extraction system. This allows the user to set a maximum RH level and outdoor temperature and the system will switch when these limits are reached. In this case the supply of air is threatened and the exhaust air is controlled by volume. In case outdoor conditions are too high the system can precool and or dehumidify the supply air.

<table>
<thead>
<tr>
<th>Judgement</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Temperatures of adaptive thermal comfort model are comfortable</td>
</tr>
<tr>
<td>+</td>
<td>For uncomfortable outdoor conditions, RH and temperature</td>
</tr>
<tr>
<td>-</td>
<td>Not passive</td>
</tr>
<tr>
<td>-</td>
<td>Necessity to have two systems, natural and mechanical ventilation</td>
</tr>
</tbody>
</table>

Table 6.4 Concurrent ventilation strategy positive and negative characteristics

External performance factors

The design is depending on outdoor conditions in order to operate in different operation modes. The following parameters are included in the design.

- Radiation
- Wind speed
- Wind direction
- Clouds
- Temperature
- Humidity
- Work hours (9:00 – 18:00)
- Height (logarithmic wind scale)

Design limitations

Draught

Due to flexibility the flow cannot be controlled inside the office. Though a personalized flow can be more optimal the depth of the office box will reduce these effects as the airflow cannot be higher than 1.5m/s and thus won’t be sensible in the middle in the office. Design model.
Temperature

Table 6.5 Mean monthly temperature

<table>
<thead>
<tr>
<th>Period</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>26.7</td>
<td>27.2</td>
<td>27.2</td>
<td>28.1</td>
<td>28.2</td>
<td>28.5</td>
<td>27.8</td>
<td>27.8</td>
<td>27.2</td>
<td>27.5</td>
<td>26.7</td>
<td>26.3</td>
<td>27.5</td>
</tr>
</tbody>
</table>

- Upper temperature limit \((^\circ C) = 0.31 \cdot \text{(outdoor air temperature)} + 20.3\)
- The possibility to raise the comfort temperature with 1 degree by 0.275m/s airflow (not for the first 0.2m/s).

Relative humidity

One of the controls to anticipate the local office culture is to manipulate or control the relative humidity in the office. As they are used to normal humidity levels (40%-70%). A limit of relative humidity can foresee problems with the lack of evaporative heat loss of individual occupants.

![Graph showing relative humidity and comfortable hours](image)

*Figure 6.6 Upper limit of relative humidity and its corresponding amount of comfortable hours within this limit for Singapore. Total amount of office hours per year is 3650 hrs.*

In total the amount of work hours between 9:00AM – 6:00PM are 3650 hours. This will be the reference with a value of 100%. During these hours there are **2557 hours** of which the humidity is even to or below 80% relative humidity (83% of the total amount of hours there is a comfortable relative humidity level). In these hours it is possible to apply cross ventilation.

By using a limit of 80%RH it can be assumed that ‘normal’ conditions are possible and thus the effects of high humidity are neglectable. Higher levels of humidity are definitely possible, in other countries which are less reliant on air conditionings it is acceptable (India and Thailand). For tropical countries with high amount of installed HVAC systems
there is less known about comfort in free running buildings, when cooling systems are off duty.

Higher RH limit contains the risks of discomfort, a lower limit has the risk of adapting too much to the current office design with intensive use of the HVAC and not applying the adaptive comfort model.

**Test case office building**

As test case building a building of 300 meters in height, 45 meters wide, and 15 meters in depth. This is based on the 1:3 ratio that is advised by Ken Yeang in his bioclimatic skyscraper approach. Test offices are situated in the middle of the floorplan at floor heights 10, 50, 150 and 250 meter. They indicate what the development for the full office will be. The test offices have the depth of 15 meters, 4 meters floor to floor height and the width of the office 5.4 meter.

![Figure 6.7 office floor plan. 15 meters depth, 45 meters wide. Each office is within the column structure of 5.4 meters.](image)

**Window wall ratio**

In order to maximize the potential savings on energy for cooling the best way should be with big chimneys and adjustable flaps in the façade. These systems require large area of the façade. For indoor environment visual contact with the outdoor environment increases the moral of the occupants. For this instance, there should be part of the façade transparent to stimulate visual contact.

To maintain optimum indoor environment no more than 60% of the horizontal part should be opaque. The windows can start higher, but a minimum of 30% of the façade surface per office, floor to ceiling height, should be transparent or a window. This value is advised for normal glass façades and not based on literature research and proven values.

![Figure 6.8 Window wall ratio limit of 30%](image)
Process limitations

Mass flow calculation

The design is not calculated for urban canyons, wind vortexes, turbulence and gusts. Surrounding buildings and flexible office design will influence the effective airflow radically and should therefore not be taken into account as possible cooling factor. For this reason, calculations are based on the volume mass flow, one side in one side out, in order to calculate the necessary volume for replacement to prevent overheating.

Figure 6.9 Calculation is based on mass flow, the volume that gets in will go true the office.

Metrological data

Design is based on an imaginary high-rise office building to give an overview on possible energy reductions for optimal orientation. Data for wind, wind direction, clouds and solar radiation and lamination are from the standard EPW files used by the Climate Consultant computer program. Unfortunately provided wind data for wind are not completely equal to a location down town Singapore due to the lack of data onsite. Other climate data may be accounted for as correct due to the close distance to the measurement positions.

HVAC saving

This fuel saving is covered with the energy saving potential. The potential of savings in relation to the current situation. Currently the office uses AC for all office work hours. If it is possible to put one hour the AC of there is a saving of 1 AC hour. In some cases the natural ventilation is not sufficient, not enough wind, too much people in the office, etc. Then it is possible to assist the mechanical ventilation with the natural available pressure as percentage of the needed capacity. Sometimes the outdoor conditions don’t allow the façade to be permeable, then the AC functions on the background to provide cold air. When the AC is working in the background this will be more energy intensive than with solely mechanical and thus should there be way to sum up the NV assistance as part of the energy saving.
Table 6.6 Energy saving potential categories and factors in relation to the remaining wattage needed to keep background AC running.

<table>
<thead>
<tr>
<th>Categories</th>
<th>NV</th>
<th>NV + fan</th>
<th>NV + AC</th>
<th>AC</th>
<th>Hours without HVAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>1</td>
<td>⅓</td>
<td>¼</td>
<td>0</td>
<td>3650 hrs. (100%)</td>
</tr>
<tr>
<td>Energy required</td>
<td>0 W</td>
<td>500 W</td>
<td>750 W</td>
<td>1000 W</td>
<td></td>
</tr>
</tbody>
</table>

Four different grades in energy saving potential are used; solely natural ventilation, natural ventilation with fan support, natural ventilation with centralized cooling, and centralized AC (table 6.5). The ratings are assumptions and are savings can be different for each office building. Depending the current state of the installations, façade status and settings. Following figure shows an example of the calculation.

Figure 6.10 Energy saving potential in hours per year. 3650HRs = 100% of the time NV is possible. Example calculation is not the actual saving potential for final design.

In the energy saving potential diagram there is a small advantage for NE-SW direction based on the NV potential. When combined with mechanical support the system the East-West orientation gives a slight advantage. Although these difference seems to be small, the difference of 0.1% of the 3650 office hours a year, saves 73 hours in 20 years, at least 8 full working days.

The sum of the amount of hours in each category is multiplied by the factor. This sum is the actual amount of hours energy is saved. This gives the design a different outcome as it is relying on a complete year of savings, and not just the current moment. Maybe this can only be achieved by helping the system with a mechanical system, but a system that
needs 10% mechanical supports for 100 days is more efficient than a system that works 20% of the time solely on NV and the rest of the time it supports 5% (90 vs. 24).

The values for calculating the weighted HVAC saving hours are assumptions. Further research should indicate if these values are correct. The values are dependent on the current state of HVAC system, age, maintenance etc., and therefore hard to judge. The values 1 for full natural ventilation, ½ for mechanical support, ¼ for mechanical support and mechanical supply. Cooling is done when no HVAC hours are saved.

Assumptions

Wind pressure coefficients

Pressure coefficients for buildings are derived from wind tunnel tests. In this thesis the values are derived from an aerodynamic database of high-rise buildings. Pressure coefficients are then taken and applied for each wind direction and different height. The influence of wind true the building is therefore neglected. For model analyzation in Design-Build the pressure coefficients are only valid for low-rise construction, but is used for this thesis as well.

Discharge coefficients

The façade openings have the same complexity as the wind pressure coefficients and are different for each situation. The values for this thesis for the window and vents are from literatures but can have different values in actual design.

Façade functions

To clearly understand or improve a construction, awareness is needed to define which parts, components and elements are related to the builder or the user of a façade; and which relate to technical or architectural functions. The façade functions tree of Klein has 5 function categories with increasing level of detail: Main function, primary and secondary functions, supporting functions, and detailed supporting functions (Klein, 2013). The tree supplies all the functions necessary for a well-functioning façade. A selection of the primary and secondary functions that are relevant for this design are shown in figure 6.11.

The relation between functions is clearly visible in the tree, as some functions are double this means that it is in interest of multiple primary functions. The main function for an office building should be the separation and filtering between nature and interior spaces, as defined by Klein.
Must be noticed that the tree is defines requirement. What can be used during the design phase to oversee functions that have influence on the design, but have not been thought by the design team. But it doesn't imply any priorities; is it more important to maintain a comfortable climate than the generating of energy? To specify the actual façade requirements and limitations, a separation of façade components needs to be done. This however is depending on the functional performance of the façade and leading to a visual circle. To make decisions the functions will first be explained to get an overall idea as base for the concept development.

**Functions**

In this thesis the focus will be on the following functions:

- **Allow reasonable building methods**

  **Structural**

  For the structural part of the façade there are several options. But there is the limitation of installation on high-rise buildings. The façade must transfer their own dead load plus any live loads, which consist primarily of positive and negative wind loads, but might also include seismic loads, maintenance loads and others. The width and the depth of the system is limited and should be taken in to account.

  **Transportation**

  The transportation of the façade should be easily done without the help of the big crane on site. This means that the module is restricted in size to fit within the elevator shaft.
and efficient volume for the transportation to reduce the amount of transport from façade contractor to building site.

**Installation**

Panels should be manageable and installed without help of the main crane. Simple installation and prefabrication is preferred. Preferable with a system that has the same distance between panels and a maximum of two brackets per segment.

**Provide a comfortable interior climate**

The temperature and humidity are important for the indoor experience. The façade should be able to react on outside conditions when possible. This means that separation from outside is possible, but that completely sealed requirements are there as well.

**Responsible handling in terms of sustainability**

*Minimize energy losses*

The main goal of the façade is to reduce cooling demand for the HVAC system. The HVAC saving hours should be one of the top priorities in the design. The façade should prevent the loss of energy when possible, the building management should monitor this closely in which the façade has to react.

*Gain energy*

Wind and stack pressures are collected. The façade should optimize the collection by using the wind wings, wind openings and the louvre windows to guide the flow. Heat collected in the chimney should be used without the loose of too much pressure. Flat surfaces and low resistance openings.

The design should be adaptive for different orientations and heights. According to local wind and radiation the façade can have sub optimization. There should be flexibility in the façade design that can optimal use the changing environment along the perimeter of the high-rise.

**Support use of the building**

*Flexibility - future floorplan*

The design should be adaptive for different orientations and heights. Future changings in floor plan and small changes shouldn’t influence the thermal comfort. To foresee in future changes cooling generated by airflow should be minimal as changes can reduce this flow.
**Self-control**

Good building management system where the occupant has sufficient control, or at least the optimal benefits from the adaptive thermal comfort. Windows needs to be operable to have the idea of self-control.

**Spatial formation of façade**

**Air mixing**

The effect of air mixing can be important for the air temperature. It is hard to predict the performance of a natural ventilated system, but the distance from the diffuser will be less due to the low pressure difference and small temperature difference.

**Daylight spreading**

Visual discomfort should be avoided, spreading of daylight and thus window spreading should take care of this. Together with flexibility the daylight factor should homogenous. As 30% demand for the functioning of occupants. More should be better as it is closer to their current glass boxes.

**Architecture**

The design of the façade is based on the influence of HVAC saving hours for this instance it is there to give an overview for future architects to make esthetics decisions. If there is no direct relation between performances the validation factors can embrace architecture as valuable for the design.

**Costs**

Feasibility is a broad applicable and should be a factor on the background. Everything is can be made but expenses have a limit. It is therefore already in the judgement of fabrication, installation and structure. In practice this is the most important driver for façade design. In an interview with façade builder Scheldebouw, it was clear that the costs of extra gaskets etc. are saved in the final design and the use of standardized profiles is the only way to be competitive.

**Operating**

The costs for installations such as fans, operable windows can be decisive. Next to the costs there is the complexity in the building management system what should be minimized. Less is more, should be for the amount of installations. In some cases the solution can mean a certain saving and the situation has to be evaluated.
6.4. Concept design

The concept is a translation of the design definition, based on literature research and conclusions made in previous chapters. The design is based on the following steps:

Table 6.7 Fundamental steps for design concept

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun shading</td>
<td>Cross ventilation</td>
<td>Solar chimney</td>
</tr>
<tr>
<td>Fixed external lamellas horizontal &amp; vertical</td>
<td>Lamellas are used to catch wind</td>
<td>Space between lamellas is used to make a chimney</td>
</tr>
<tr>
<td>Blocking of high and low sun position</td>
<td>If outdoor conditions are comfortable (humidity &amp; temperature)</td>
<td>If outdoor conditions don’t allow cross ventilation (humidity, wind)</td>
</tr>
<tr>
<td>Reducing interior radiation &amp; interior surface temperature gradient</td>
<td>Wind, wind speed, direction</td>
<td>Radiation, internal heat load, wind pressure</td>
</tr>
</tbody>
</table>

The concept is formed by the need for cooling load reduction. This is done by external shading and the adaptive thermal comfort when outdoor, humidity and temperature, conditions allow it. For the remaining time, when outdoor conditions don’t allow natural ventilation, a concurrent mixed mode strategy is applied where HVAC system is running on the background. Supported by passive solar chimney exhaust which operates on wind, radiation and internal heat load. The geographical location and local climate can be optimal used when opposite facades are symmetrical, to use the sun and wind 365 days a year.

Figure 6.16.1 Design concept: section simplification with building management system. Based on outdoor conditions and occupants’ preferences. NV via solar chimney and cross-ventilation.
The existing HVAC system is maintained. Where the façades now are now part of the climate system. All controlled by the Building Management System (BMS); depending on the external factors: wind, humidity, temperature and radiation. These external factors are monitored together with preferences and internal sensors the building can operate it in a desirable way for occupants. Where possible natural ventilation is used, but always the final control is for the occupants.

The design concept is showing the verticality of the chimneys. The transparency is decreased but this is compensated by lack of discomfort as glare by shading and operable windows.

**Concept functionality**

Wind and sun are changing from direction time to time, as well as the intensity. Sometimes wind and sun are summed up, sometimes only one is sufficient. To maintain thermal comfort at all times, mechanical and concurrent mixed mode modes have to be implemented. These modes should be managed by the building management system to operate in full potential, but always there should be the manual override option. There are over 30 individual modes based on outdoor conditions. Based on external performance factors these can be categorized in five main operative modes:

1. Cross ventilation mode
2. Stack ventilation mode
3. Combination of cross and stack
4. Mixed mode – mechanical
5. Mixed mode – concurrent cooling / dehumidifying

---

*Figure 6.13 Façade concept; cut out of high-rise façade. Verticality expressed chimneys with external horizontal shading.*

*Figure 6.14 Façade concept; Inlets and outlets play a role in the architecture.*
Main operative modes

Cross ventilation

For cross ventilation there are two possibilities, the sun can help to create a higher flow or when the sun is acting on the same side as the wind inlet.

![Cross ventilation mode for different wind positions](image)

*Figure 6.15 Cross ventilation mode for different wind positions*

Stack ventilation

Due to the diffuse light in Singapore, it may be possible that there is radiation on both opposite chimneys, or that there is negative pressure on one and radiation on the other. In case the chimneys can work together to achieve a better result. In case reverse stack effect occurs the system should close the chimney to prevent warm air getting in the office. There are four options for wind in case the sun is right; wind from side, no wind, wind from left, wind from right.

![Stack ventilation mode with different wind directions](image)

*Figure 6.16 Stack ventilation mode with different wind directions*

Combination of cross and stack

If there is not sufficient wind available to ventilate with only cross ventilation and not sufficient stack effect to get the required volume flow the flows can be combined. In this case both system can work together to establish natural ventilation, and no need of background cooling is demanded from the HVAC system.
By increasing the amount of supply surface and exit surface the volume is regulated. If there is small delta T, larger volumes are needed to remove the heat. Depending where the occupants are in the floorplan the system can adjust. As the low-vents have influence on the occupants close to the perimeter etc. If wind and chimney are from the same site, the chimney is not working, as t

Mixed mode – fan support

In mixed mode the passive ventilation is supported by a fan in the chimney to produce the necessary pressure difference. This is in case wind and sun, or a combination of both is not able to create the required pressure difference.

Mixed mode – AC support

Another function is for the mixed mode is when outdoor conditions don’t allow cross ventilation and conditioned air is supplied via centralized ventilation duct. This air is only cooled if outdoor temperature is too high as well.
The above schemes show the possibility of conditioned air supply and the passive extraction ability. This is only possible if the sum of the energy loss by open windows is smaller than the power needed to extract the air mechanically.

**Building management system (BMS)**

To manage the full potential of the natural ventilation strategy the BMS needs to be operating the opening of the windows, the aperture of the diffusers and the nozzles. Due to the changing effects of the external performance indicators it is necessary to have a well-functioning smart system that can benefit from external conditions.

**Sensors**

To benefit from external conditions, the system must know the expectation and the planning of the occupants; If the office will be empty within an hour, the people can accept higher temperatures and therefore the AC can be not necessary. With this knowledge the system can optimize its settings based on current conditions and calculate a ventilation plan for maximum saving potential and still maintain comfort.
Exterior

To ensure the comfort is maintained up to date weather information is a necessity. As it is unknown what the temperature will be at the top of the building (or halfway etc.) each segments needs its own sensors to prevent a higher or colder indoor temperature than is calculated, as humidity is more homogeneous less humidity sensors will be needed. Wind pressure coefficients tend to give different readings across the façade which makes these more frequent installed. Regarding temperature, this should be monitored closely, as heat columns can cause higher temperatures on some spots.

Interior

Interior sensors should notify where the people are seated in order to adjust the airflow where needed. As the personal comfort zone should be optimized in terms of thermal comfort other spaces can have less comfort.

Interior temperature, air quality, and humidity should be monitored. Where the inlet of the exhaust system can be a good spot to place the sensors. In this case there can be zones monitored, and in combination with a mobile application for thermal comfort, settings can be learned to the system.

Heat column

Due to thermal buoyancy a heat column is created in the perimeter of the façade. This extra heat load can cause increase in outside temperature and can cause discomfortable situations ($T_{\text{outdoor}} > T_{\text{comfort}}$).

Table 6.8 Influence of heat column

<table>
<thead>
<tr>
<th></th>
<th>No preheating</th>
<th>Air is preheated</th>
<th>Air is too warm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{incoming air}}$</td>
<td>$T_{\text{comfort}}$</td>
<td>$T_{\text{comfort}}$</td>
<td>$T_{\text{comfort}}$</td>
</tr>
<tr>
<td>Wind + sun</td>
<td>$T_{\text{comfort}}$</td>
<td>$T_{\text{comfort}}$</td>
<td>$T_{\text{comfort}}$</td>
</tr>
<tr>
<td>Airflow is used to remove excessive from office</td>
<td>Larger airflow is needed to remove excessive heat from office</td>
<td>AC on, extracting can be done with the negative wind pressure on leeward side</td>
<td></td>
</tr>
</tbody>
</table>

The heat column occurs only when the wind and the sun are from the same direction. With a prevailing north-south wind, with a building orientation on north-south. Depending on surrounding objects if the heat column occurs. For Singapore there will be influence of the heat column as for summer situation, June – Oct, prevailing wind is from...
south direction. Sun is on the north side. Winter situation, Nov – May, with prevailing wind is from north direction. Sun is on the south side.

**Adaptive thermal comfort**

The application of the adaptive thermal comfort increases the comfort temperature according to the satisfaction of the occupants. In order to realize this, windows need to be operable and preferences should be used to organize the demand in the most efficient way.

**Operable windows**

There are several situations where an open window can create an opposite effect, and thus affecting the performance of the façade. This should be prevented when this is possible, and even if the windows are manual controlled the windows should be able to close automatically. Possibility to open the windows and program them to close after 2 hours can be a simple addition, as people will open a window but forget to close it.

**Table 6.9 effects of open windows when this is not desired**

<table>
<thead>
<tr>
<th>Wind – sun</th>
<th>Wind + sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Contaminated air can enter</td>
<td>▪ Conditioned air is lost</td>
</tr>
<tr>
<td>▪ Too warm air can enter</td>
<td>▪ Humidity level uncontrolled</td>
</tr>
<tr>
<td>▪ Heat losses increase when AC is on</td>
<td></td>
</tr>
<tr>
<td>▪ Humidity level uncontrolled</td>
<td></td>
</tr>
</tbody>
</table>

**Personal preferences**

With cross ventilation, space close to the open windows, the airflow will be higher. This can be desirable for some occupants, for other not. These personal preferences can influence the efficiency. People that feel easier cold, warm etc. should be placed in different zones. If occupants have self-control, they by using their mobiles to adjust the settings the system knows the preferences of each individual. This data can be used to organize the work efficiency and people can be shifted from
one place to one close by which better suits their thermal preferences.

Contamination

When wind and sun are from the same direction, the chimney’s exit will heat up the air and the wind will lead this air into the office. As this air is contaminated the system should shut off of rising and should be prevented of entering the building. Some air quality check needs to be done. As natural ventilation has higher volume rates the problem will be less dramatically, but can still have influence as its piling effect for a tall office building. It is in line with heat column effect.

![Figure 6.22 Contamination. Dirty air should be prevented from entering.](image: http://www.slideshare.net/arkam_slideshare/)

In normal conditions this will not occur often as wind pressures spread around the building, making the flow in all the offices in the same direction.

Coanda effect

The Coanda effect creates a change in pressure at the parallel surface due to limited access for air to replace the entered air above the flow. It allows airflow to cling to the ceiling it is flowing with. As the airflow moves along the surface, its movement is extended along that surface and projected farther into a room or down a duct than it would if it were blowing into an open space.

![Figure 6.23 Coanda effect created by the inflowing air.](image: http://www.slideshare.net/arkam_slideshare/)
The air moving with the surface needs a smooth, obstruction-free pathway to maintain the Coanda effect. Any disturbance to the airflow pathway has a dramatic impact on the extended airstream being maintained. On a ceiling, items such as light fixtures or ceiling variations are obstructions and will interfere with the airflow being maintained (Benjamin Bronsema, 2011).

The Coanda effect can be used to increase the throw distance of the cross ventilation, this allows higher velocities to enter the office as this won’t disturb the occupants close to the façade.

Wind gusts

Wind is needed to create pressure differences along the facades however, this is only desirable when there is control. With wind gusts the flow can be disturbed and negative side effects can cause dissatisfaction. Wind protection is therefore needed to maintain maximum airflow velocities.

Opening surface area

When cross ventilation is applied, the effective surface area should be bigger on the exit side than the entrance side. As wind pressure is restricted by the opening resistance, the resistance is lower as the opening area is bigger. As the speed is defined by the entrance, based on preferences of the occupants the flow will reduce its speeds on its path. This path can be optimized by smoother and thus less friction route. Simple increase of exit area can improve the flow.
Concept design components

The concept consists of 2 façade components, solar chimney and the cross ventilation segment with horizontal lamellas in front. In the interior we can signify the components of the ducts, and a building management computer to arrange the hybrid mode.

To create a validated design, the different components need to be combined and optimized in order to fulfill the design process. The efficiency of the design is dependent on the inlet and outlet of the system, the façade, and the actual effectiveness is as well dependent on the functioning of the system. Therefore, the design is split up in the façade design components and the climate design components.

Concept façade design components

The facade can be separated in three components, chimney, external shading and wind component which contains a high vent, operable window, and a monsoon vent. Together they form the façade design.

Solar chimney façade component | Wind façade component | External solar shading

Figure 6.27 Façade components

Concept climate design components

The system is evaluated on the performance and the validation factors. Therefore, the system performance factors should be taken in account as well.
Sub-components

Each component is build up out of several sub-components which will interfere with each other in performance. Therefore, it is necessary to process the individual components to look for an optimal façade composition.

Vertical fins

- Wind wings, outside of the solar chimney sides deflect the wind towards the openings in the wind façade component. This will improve the inflow by increasing the pressure difference. The positive pressure produced by the wings will increase volume flow true the office.
- Vertical Shading, vertical fins bring shade on the façade behind it as well. For areas close to the equator vertical fins are good for blocking the low sun during the morning and late afternoons.

Horizontal lamellas

- Horizontal shading to block the high sun. This radiation is during the heat peak from 13:00 and 16:00. Although this won’t win any HVAC saving hours as outside temperature is not comfortable, but will reduce the cooling load by reducing the radiation.

Monsoon vent

- The low vent is there to maintain temperature during off work hours, during monsoon rains and if temperature allows it can be used for cross ventilation. For the chimney this vent will be important as it is the maximum stack height it can give to the chimney.

High ventilation vent

- The high vent above the windows enables an air to enter the office after reaching the façade perimeter. The duct can be seen as a normal ventilation duct where the air is distributed over the office space where it is needed. It can function as air supply for the stack ventilation and can improve the cross ventilation.

High operable window

- High windows enable an airflow that is not interfering with the personal area of occupants. As the airflow will stuck to the ceiling and after a few meters speed decreases and air mixing takes places. The heat is extracted from the office with this high flow.
Low operable windows

- Self-control. The lower windows are for personal use and take not active part in the ventilation system and enables occupants to open windows for their own comfort zone.
- Relation with the outdoor environment

Solar chimney

- Stack effect. The solar chimney enhances solar induced stack effect and uses the height to extract air from the office.
- The depth of the chimney is used for shading of the office window.
- The chimney is used as vertical fin to catch wind.

Lowered ceiling

- Improving the Coanda ‘stick’ effect. The lowered ceiling is a complex network for ducts. Inlets and outlets run for the full depth of the office. By using the ceiling as guide for the airflow in the office it can prevent discomfort.

6.5. Performance of facade design components

The lack of natural ventilation design in tropical high-rises makes the concept an idea without any fundamental grounds other than literature and references.

The façade design (sub-) components have individual efficiency curves. To explore the best composition, it’s necessary to know what the optimum for each variable is. As external factors have an influence on the design, the best design is based on these external conditions. Therefore, orientation is one of the critical conditions which are explored to identify the best and or worst position for the building.

Performance calculations of the chimney and wind façade with the external factors of Singapore gives an overview of the performance, effective hours of energy saving, in relation with the variable.

Table 6.10 Variables and symbols

<table>
<thead>
<tr>
<th>Name</th>
<th>symbol</th>
<th>value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric flow</td>
<td>Q</td>
<td>-</td>
<td>m³/s</td>
</tr>
<tr>
<td>Discharge coefficient</td>
<td>C_d</td>
<td>0.6 - 1.0</td>
<td></td>
</tr>
<tr>
<td>Effective surface area</td>
<td>A_e</td>
<td>-</td>
<td>m²</td>
</tr>
<tr>
<td>Temperature difference</td>
<td>ΔT</td>
<td>-</td>
<td>°C</td>
</tr>
</tbody>
</table>
The performance is calculated as the partial of required volume change at the certain moment. Depending on the outdoor temperatures and the relevant comfort temperature for that time the necessary volume flow is calculated with maximum allowed heat absorbance for that time. In this case the indoor temperature is never higher than the allowed upper limit of 10%PPD. Demand is calculated by,

$$\text{Demand } Q = \frac{200W \times (12 \text{ occupants}) \times 3600s}{e_{\text{air}m^3\text{office}}(T_c-T_a)\text{m}^3\text{office}} \times \frac{3600s}{m^3/s} = m^3/s$$

**Cross ventilation performance**

The wind facade component consists out of 4 different openings; high vent, low vent, louvre windows and an operable window. Each opening has its own characteristic discharge coefficient. Together with the opening are the effectiveness can be calculated via the hydraulic diameter of each individual opening.
Initial concept consists of 5 wind façade components per office per side. Windows are in series and can be add up by the effective area formula only the discharge coefficients stay the same for variable window dimensions. The influence of the hydraulic diameter is the reducing factor in effective surface area. The optimum effective area is depending on the height of the operable windows. For the design the maximum opening area for cross ventilation is limited by personal comfort as wind cannot have direct access to the work surface.

In the calculation there is no difference between flow directions. Cross ventilation goes from negative to positive pressure field and only the volumetric flow is monitored. Due to symmetry, opposite sites contain the same opening area. The effect increases when negative side contains a bigger opening area, this will be in the actual design but not included in the mass flow calculation, as direction is no direct influence.

Effectiveness is influenced by external performance factors, wind and its direction, outside temperature, relative humidity and the height of the floor according to the wind-log and its pressure coefficients. Only when outdoor conditions are acceptable cross ventilation is used.

Wind pressure is calculated via the pressure difference over the opening and the reference wind speed.

\[
P_{\text{wind}} = \frac{1}{2} \rho v_r^2
\]  

The reference speed is obtained from the wind at the metrological weather station and translated to the wind height at 300 meters height of the building.

\[
v_r = V_{\text{ref}} \cdot \left(\frac{400}{10}\right)^{0.17} \cdot \left(\frac{300}{400}\right)^{0.33}
\]
In order to get a certain flow true an opening the pressure coefficient which is derived from the pressure differences between windward and leeward is applied (figure 6.30)(sheet with coefficients for directions and height in the appendix) (University).

\[ \Delta P_w = \frac{1}{2} \rho v_r^2 \cdot C_p \]

All the parameters for the cross ventilation are known at this moment and now the calculation for the airflow can be done.

\[ Q = C_d A_e \sqrt{\frac{2 \Delta P}{\rho}} \]

In this formula the discharge coefficient is used in the effective surface area for the individual openings and again, this time to simulate the primary pressure losses. This is not the usual way to compensate for friction losses in an office. But due to the depth of the office the duct is somehow limited and to deal with future changes this has to be with high friction. By applying the 0.65^3 as reduction factor for compensating the pressure losses this is done.

For the performance of the chimney the dimensions should be in height in line with figure 6.7. The variation in the performance can be due to the discharge coefficient of the office and the width of the element. As the relation between surface areas is clear (figure 6.31). The performance will be done for 4 segments per office façade.
Discharge coefficient $0.65^3$

Table 6.5 Variable width of wind façade component. Four segments per façade with high resistance discharge coefficient for the office.

<table>
<thead>
<tr>
<th>Wind façade; 4 x segment 1.35 Cd vents 0.80, Cd window 0.85, Cd office 0.65</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor altitude</td>
</tr>
<tr>
<td>North-South</td>
</tr>
<tr>
<td>East-West</td>
</tr>
<tr>
<td>Northeast-Southwest</td>
</tr>
<tr>
<td>Northwest-Southeast</td>
</tr>
</tbody>
</table>

The performance of the wind façade varies from 138 to 265 hours HVAC saving. This is due to the prevailing wind direction North-South. This direction might be a bit more towards the west as northwest-southeast scores the best. For the same reason the East-West and Northeast direction score lower.

All graphs seem to be declining a bit after 0.5 meter. Due to the limited amount of hours where it is possible to use cross ventilation. The height difference is bit more clearly than with the stack ventilation. 250 meters scores the best, only for Northeast-Southwest is it the lowest.
Discharge coefficient $0.90^3$

Table 6.6 Variable width of wind façade component. Four segments per façade with low resistance discharge coefficient for the office.

<table>
<thead>
<tr>
<th>Wind façade; 4 x segment 1.35 Cd vents 0.80, Cd window 0.85, Cd office 0.90</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor altitude</td>
</tr>
</tbody>
</table>
| North-South | ![Graph](image1)
| East-West | ![Graph](image2)
| Northeast-Southwest | ![Graph](image3)
| Northwest-Southwest | ![Graph](image4)

There is clear relation visible between discharge coefficients and the HVAC saving hours. This is clearly due to the increase in volumetric flow. This can have two possible reasons.

1. Increase in comfort temperature. With the lower resistance it is easier to get higher velocities and the increase in comfort temperature increases the amount of possible HVAC hours.
2. Increasing heat capacity. With a bigger flow the heat capacity increases. This has the potential of allowing higher temperatures.
A combination of both is probably the cause in the high scores. But for a real office location and a depth of 15 meters there will be friction, and thus the scenario with the high discharge coefficient 0.65 will be more realistic. Further research in the ability of flexible office floor plan and wind resistance can bring a better insight, for now the value of 0.65 will be used.

Effectiveness vents for office $0.65^3$

Table 6.7 Wind façade component with only operable vents with high resistance of office.

| Wind façade; 4 x segment width variable, Cd vents 0.80, NO windows, Cd office 0.65 |
| --- | --- | --- | --- | --- |
| floor altitude | 10m | 50m | 150m | 250m |
| North-South | | | | |
| hours without HVAC/year | 127 | | | |
| width of segment [m] | 0.0 | 0.5 | 1.0 | |
| East-West | | | | |
| hours without HVAC/year | 79 | | | |
| width of segment [m] | 0.0 | 0.5 | 1.0 | |
| Northeast-Southwest | | | | |
| hours without HVAC/year | 62 | | | |
| width of segment [m] | 0.0 | 0.5 | 1.0 | |
| Northwest-Southeast | | | | |
| hours without HVAC/year | 136 | | | |
| width of segment [m] | 0.0 | 0.5 | 1.0 | |

The pattern shows similar curves with lower values. The performance per orientation stay similar. For the Northeast-Southwest orientation the 250 meter is higher than the
other altitudes for this orientation. What is unusual and the conclusion can be that for lower speeds this height scores better, but less important as differences are still minimal.

Northwest-Southeast, stays the highest and is more than double the lowest scoring orientation.

Operable windows for office $0.65^3$

Table 6.8 Wind façade component with only operable windows with high resistance of office

The scores are higher than with only operable vents. This is due to the lower resistance for the discharge coefficient.
Patterns show similarities with previous wind charts. With 250 meter normally as highest score per orientation.

Cross ventilation conclusion

The HVAC saving effect is in direct relation with the operable surface. This is partly due to the not adapting primary and secondary pressure losses. The high pressure loss of the office is in line with the flexibility and depth of the office, where obstacles can cause extra pressure losses. The functionality of only vents or only in windows is not advisable as cooling is improved by higher volumetric flow.

With the maximum openness and the score will be somewhere between 250 – 350 hours of HVAC saving for the highest ranked orientation. With this saving of 7% during working hours confirms that cross ventilation is effective in this climate. All graphs show a preferred north – south orientation of the building, where height is of less influence. For further optimization the breeze should be optimized to minimize losses on its path and maximize the mixing potential.

Solar chimney performance

The working of a chimney; on its way the air temperature rises and speed will increase due to the expanding volume. Friction will temper the flow and pressure losses in its path should be minimized. Flow (Q) is by the remaining pressure differences between inlet and outlet.

\[ Q = A_e \frac{2\Delta P}{\rho} \]

The flow goes from positive to negative pressure fields. The pressure difference is the relation between wind pressure, stack pressure, pressure loss due to friction in the chimney and pressure loses due to openings or valves according to the following equation.

The sum of the different pressures is depending on velocity in the chimney, as the losses are multiplied by the factor \( \frac{1}{2} \rho v_m^2 \).

\[ \Delta P = P_{wind} + P_{Stack} + P_{loss\ primary} + P_{loss\ secondary} = P_{wind} + P_{Stack} + \frac{1}{2} \rho v_m^2 \cdot \sum K_{drop} \]
As the speed is depending on the volumetric flow divided by the surface area the following substitution can be made,

\[ v_m = \frac{A_e}{A_e} \sqrt{\frac{\Delta P}{\rho}} = \sqrt{\frac{2\Delta P}{\rho}} \]

This will lead to the iterative function of the pressure equation,

\[ \Delta P = P_{\text{wind}} + P_{\text{Stack}} + P_{\text{loss total}} \cdot \frac{1}{2} \rho \left( \sqrt{\frac{2\Delta P}{\rho}} \right)^2 \]

This equation can be solved by using a circular equation where the input is the output. This sequence is repeated until the result is within the deviation boundaries.

The friction factor and the speed are the two unknown values in the equation, as the parameters of the chimney can be selected and tested until the outcome fits within the requirements. The friction factor is based on the speed via the Reynolds number and the material.

Primary pressure loses by the duct,

\[ P_{\text{loss primary}} = \lambda \frac{L}{D_h} \cdot \frac{1}{2} \rho v_m^2 \]

\[ \lambda = \frac{e}{(-2 \log(e^{3.72D_h + 5.74} / (Re)^{0.801}))^2} \]

Where the flow characteristics are derived by the Reynolds number,

\[ Re = \frac{v_m \cdot D_h \cdot \rho}{\nu} \]

To oversee in what range the Reynolds number will be, the graph is plotted for different hydraulic diameters and different velocities.
Figure 6.32 Reynold numbers curves for different hydraulic diameters

Highest value is around 600,000, the lowest value was found was 2,340 for a chimney with a hydraulic diameter of 0.2m and an average velocity of 0.2m/s. As this speed in combination with its volumetric capacity is way too small to serve for the purpose, it is clear that the flow in the chimney will be turbulent (>3,000). Reynold numbers expected to be in the range from 20,000 – 300,000.

The roughness factor will be in range from 0.015 – 0.0015 mm (glass – steel). The friction factor is an indicator for the primary pressure losses. These losses will increase in height and are normally expressed in pressure losses per meter.

Secondary pressure loses for openings, valves, etc.

\[
[EQ 1.] \quad P_{\text{loss secondary}} = \left( C_{D1} \left( \frac{A}{A_1} \right) + C_{D2} \left( \frac{A}{A_2} \right) + C_{Dn} \left( \frac{A}{A_n} \right) \right) \times \frac{1}{2} \rho v_m^2
\]

Wind pressure on the exit of the chimney. As the pressure in the office is assumed to be zero, the pressure coefficient is then assumed to be the pressure coefficient given by the pressure coefficients derived from tests and existing data (appendix).

\[
[EQ 2.] \quad P_{\text{wind}} = \frac{1}{2} \rho v_m^2 \times C_p
\]

Pressure generated by the stack effect,

\[
[EQ 3.] \quad P_{\text{stack}} = \rho g L \frac{\Delta T}{T_a}
\]
The solar façade/chimney/Trombe wall calculation is based on the amount of radiation, and thus the width times the height (façade surface) and height of the wall due the gravitational force that is the thriving force but wind has its influence as well and can improve or decrease the flow.

\[ \Delta T = 0.0279 \times \left( \frac{\Delta \text{Heat}^2}{L \cdot f^2 \cdot A_E^2} \right)^{\frac{1}{3}} \]

Another variable that seems important for high-rise buildings is that there is almost always wind. On big buildings the positive pressure on one side creates negative pressures on the opposite side, and the outlet of the chimney functions as an outlet towards a negative pressure field. For this the aperture of the outlet is important as well.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Height</th>
<th>Width</th>
<th>Aperture</th>
<th>Pressure loss / materialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_E$</td>
<td>$\rho g L \frac{\Delta T}{T_a}$</td>
<td>$\frac{\Delta \text{Heat}^2}{L \cdot f^2 \cdot A_E^2}$</td>
<td>$A_E$</td>
<td>$\lambda \frac{L}{D_h}$</td>
</tr>
</tbody>
</table>

*Figure 6.12 performance factors for solar chimney*

The relation of wind and radiation come clear out the equations. For the temperature the relation is not directly in the equation. By using the transmission factor of the glass there can be some kind of manipulation to implement the heat loss in the chimney. Reduction of the total amount of absorbed radiation.

\[ \Delta \text{Heat} = \text{solar radiation} \times L \times w \times \text{glass}_{\text{transmission}} \]

\[ \text{glass}_{\text{transmission}} = \text{heat transmission} \times \text{heat loss system} \]

For the effective application of the solar chimney as natural ventilation strategy the outside temperature is important. When there is sufficient radiation but outdoor temperature is too high the amount of effective hours is reduced. For this instance, the way of measuring of effectiveness is not only measured by fully NV application. It can be that the chimney supports 90% of the pressure difference and that 10% of mechanical appliances is needed. Or for instance when cooling is on, it can still function as exhaust, and thus save energy.
Static calculation

To vary in the different variables, the best option is to change one variable each time. The use of a standard chimney on which the different variables are tested is based on a simple geometry; a rectangular box with an opening in the bottom and in the top.

Basic diameters are 0.9m by 0.6 meter for all the openings. The discharge coefficients for the entrée is 0.8, section (0.9), and the exit (0.9).

\[
P_{loss\ secondary} = \left(0.8 \left(\frac{A}{A_1}\right) + 0.9 \left(\frac{A}{A_2}\right) + 0.9 \left(\frac{A}{A_n}\right) \right) \times \frac{1}{2} \rho v_m^2
\]

Figure 6.33 variables for the stack effect.

Chimney length

![Figure 6.34 Chimney length](image)

Figure 6.34 shows the relation between chimney length and the volumetric flow. The influence of the reference wind is clearly visible. If there is no wind (grey line) the chimney shows a parabolic form. The higher the chimney gets the flatter the line will be.
For a chimney height above 40 meters the flow is less efficient per meter. Depending on the wind ranging from 0.01m³/s – 0.12m³/s.

\[ \text{Flow efficiency} = \frac{Q}{L} \]

<table>
<thead>
<tr>
<th>Chimney Length [m]</th>
<th>-4 m/s</th>
<th>-2 m/s</th>
<th>0 m/s</th>
<th>2 m/s</th>
<th>4 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eff [Q/m]</td>
<td>Q [m³/s]</td>
<td>Eff [Q/m]</td>
<td>Q [m³/s]</td>
<td>Eff [Q/m]</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>0.02</td>
<td>0.03</td>
<td>0.25</td>
<td>0.04</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>0.02</td>
<td>0.03</td>
<td>0.22</td>
<td>0.03</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>0.02</td>
<td>0.02</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>0.02</td>
<td>0.02</td>
<td>0.32</td>
<td>0.02</td>
</tr>
<tr>
<td>24</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.36</td>
<td>0.02</td>
</tr>
<tr>
<td>28</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.39</td>
<td>0.02</td>
</tr>
<tr>
<td>32</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.42</td>
<td>0.01</td>
</tr>
<tr>
<td>36</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.44</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The flow efficiency in above table shows the opposite effect than was expected. Where the height of the chimney is an important variable in in the stack pressure, the other pressures are causing the flattening of the efficiency and finally the increase in flow as well. However, the static pressure losses made by the openings etc. is similar for all scenarios and may be part of the decrease effect.

In the calculation above, the same internal heat load is used, as well as the same wind pressures. The only variables that can cause the decrease are the pressure losses and the radiation per square meter for the front side of the chimney. For a façade solution, where there is limited amount of façade, it is better to have shorter chimneys as they have higher efficiency per meter.

**Pressure losses**

The initial concept with 4 story high chimney may be more efficient when it is cut into four shorter chimneys, as shorter chimneys have higher efficiency per meter. To test this there are two different designs. One design with one chimney of 16 meter, and one design with 4 chimneys of four meter.
In the calculation the internal heat load is divided by the amount of chimneys. There are 12 occupants, each good for 200W. For design one this means extra heat of 2400W, for design two, 600W. Total amount of internal radiation is the same, 2400W.

The chart shows the difference in volume flows for the designs. The reference wind has a big influence on the flows. Where the negative wind pressure creates a drop in flow for the four chimney design, the flow for the single chimney still functions as the stack pressure is bigger in the chimney. The pressure values for the graph are shown in table.

Table 6.106 Static flow values for two different designs

<table>
<thead>
<tr>
<th>Reference wind speed</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m/s</td>
<td>m/s</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td><strong>Design 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 x 16 meter chimney</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flow m3/s</td>
<td>0.52</td>
<td>0.40</td>
<td>0.30</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P_{\text{loss}}$ Pa</td>
<td>-5.36</td>
<td>-3.04</td>
<td>-2.27</td>
<td>-1.50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P_{\text{stack}}$ Pa</td>
<td>6.81</td>
<td>6.81</td>
<td>6.81</td>
<td>6.81</td>
<td>6.81</td>
<td>6.81</td>
</tr>
<tr>
<td>$P_{\text{wind}}$ Pa</td>
<td>9.28</td>
<td>2.32</td>
<td>-</td>
<td>-2.32</td>
<td>-9.28</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta P$ Pa</td>
<td>10.72</td>
<td>6.08</td>
<td>2.99</td>
<td>1.89</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Design 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 x 4 meter chimney</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flow m3/s</td>
<td>1.87</td>
<td>1.07</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P_{\text{loss}}$ Pa</td>
<td>-6.88</td>
<td>-2.32</td>
<td>-0.76</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P_{\text{stack}}$ Pa</td>
<td>4.29</td>
<td>4.29</td>
<td>4.29</td>
<td>4.29</td>
<td>4.88</td>
<td>4.88</td>
</tr>
<tr>
<td>$P_{\text{wind}}$ Pa</td>
<td>37.12</td>
<td>9.28</td>
<td>0</td>
<td>-9.28</td>
<td>-37.12</td>
<td>-</td>
</tr>
</tbody>
</table>
The difference, or actually the only similarities between the two designs is the amount of pressure losses. For the four-meter reference wind situation, the losses are almost similar, 5.36 and 6.88 Pa, but somehow this still gives a different volume flow, as the volumes are factor 3 in difference. The sum of the pressures is different, the losses are equal, there may be a different ratio in primary and secondary losses, the difference must be within the stack and wind.

The wind pressure is causing the big difference as design 2 is 3.66 times bigger than the wind pressure in design one. The big difference is not exactly four due to the iterative process where the speed is decreased in order to deal with the resistance.

**Yearly simulation**

In this paragraph the derived graphs show the results based on yearly simulation. In this simulation there are some errors that will be explained after in the discrepancy paragraph. The relations that are found are still relevant to demonstrate that natural ventilation is effective. The amount of effectiveness should be taken care with as it includes discrepancies.

*Table 6.11 variable chimney length*

<table>
<thead>
<tr>
<th>Altitude</th>
<th>10</th>
<th>50</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Max Hrs.</td>
<td>67</td>
<td>66</td>
<td>79</td>
<td>77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude</th>
<th>10</th>
<th>50</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Max Hrs.</td>
<td>59</td>
<td>57</td>
<td>55</td>
<td>54</td>
</tr>
</tbody>
</table>

![Graph showing amount of hours effective for chimney height]

![Graph showing amount of hours effective for chimney height]
The length of the chimney is not following the expected curvature where more potential saving is expected with a higher chimney. The relative small dimensions and thus the relative high friction are causing this. In solar power generators the diameter is 10 meter and the height 200 meters with a full field of heat absorbers.

The limited amount of resources cannot optimal used when extending the length of the chimney, as effective surface cannot increase further due to depth limitations. Therefore, wind and internal heat load are less effective by bigger length due the higher losses. The low radiation in-fall cannot compensate for these losses. This means that the design is not solar dependent and that the design requires a low pressure/low speed approach to maintain certain effectiveness.

As calculated in the static calculations the decrease in efficiency per meter should be clear, but this shouldn’t show the decrease in absolute numbers.

It can be assumed that the surface area is the biggest thread for the flow, this should be maximized at all times. Figure # shows the relation between amount of chimneys and the effective opening area. With two chimneys the summed effective surface is 0.60m², almost twice as big as the other two. As wind pressure is equal on the façade, this has direct relation with the surface area. Even with longer chimneys the frictional resistance increase and
flow decreases. The only advantage of the long chimney is the functioning during negative wind, where a smaller surface area has less negative effects for wind. With the prevailing wind direction and symmetry this effect is not of application in Singapore. For the rest of the design the single height chimney will be investigated.

**Chimney width**

*Table 6.12 Variable chimney width (table continues on the next page)*

As width increases the surface area of the chimney, the losses stay similar or even reduce. For a chimney 0.9 by 0.9 should be the squarest, and thus the highest hydraulic diameter ratio, this is not visible in the above graphic. It is clearly that around 1.0 m the inclination is the highest. Flattening at some point should happen, but without a decreasing in amount of effective hours.
\[ P_{\text{loss secondary}} = \left( C_{D1} \left( \frac{A}{A_1} \right) + C_{D2} \left( \frac{A}{A_2} \right) + C_{Dn} \left( \frac{A}{A_n} \right) \right) \cdot \frac{1}{2} \rho \nu m^2 \]

**Chimney depth**

Amount of airflow in the chimney is in direct relation with effective surface area of the chimney. The effective surface area is not only affected by the chimneys depth, as well the entree and the exit play a role in this surface area. When depth is increased the surface area increases what will lower the friction and thus the pressure losses, resulting in a bigger volume flow. But inclination is limited and flattens out due the fixed exit and entree height, which cannot further increase the effective surface area \( A_e \).

Table 6.176.13 Variable chimney depth (table continues on next page)

| Chimney; length 4.0m, depth variable, width 1.0m, entree height 0.5 & 0.9m |
|-----------------------------|------------------|------------------|------------------|------------------|
| floor altitude             | 10m              | 50m              | 150m             | 250m             |
|                            |                  |                  |                  |                  |

FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE | 155
Although wind is the greatest driver, pressure difference $\Delta p$, is greater in East-West direction, or at least outdoor conditions are more often in favour for this direction as it contains more hours of HVAC saving. What indicates that the prevailing wind direction is influencing the East-West direction at the same time.

The variation between the two different entree heights is no more than 20 hours on yearly base. This difference is due to the effective area difference (0.55m$^2$ vs 0.61m$^2$). And thus in line with earlier relations.
Discrepancy results

Pressure losses are calculated via a bypass to overcome the problem with circular calculations. First the flow is calculated via the corrected heat load, where the internal heat load is divided by the ratio of radiation and chimney, and wind pressure. This volume, without pressure losses, gives the mean velocity for the smallest section. The pressure losses, friction and local resistance, are based on this velocity and influences the result. Final calculated results show small discrepancy in some occasions. The main error is that it leaves results out that should be included.

<table>
<thead>
<tr>
<th>chimney</th>
<th>approach</th>
<th>( V_m )</th>
<th>( \lambda )</th>
<th>( P_{primary} )</th>
<th>( P_{secondary} )</th>
<th>( P_{stack} )</th>
<th>( P_{wind} )</th>
<th>( Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney 4m Width 0.6m</td>
<td>simulation</td>
<td>0.35</td>
<td>0.025</td>
<td>0.007</td>
<td>0.11</td>
<td>0.60</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>Chimney 4m Width 0.6m</td>
<td>calculation</td>
<td>0.6</td>
<td>0.025</td>
<td>0.1</td>
<td>0.3</td>
<td>0.60</td>
<td>-</td>
<td>0.12</td>
</tr>
<tr>
<td>Chimney 16m Width 0.6</td>
<td>simulation</td>
<td>0.4</td>
<td>0.024</td>
<td>0.04</td>
<td>0.15</td>
<td>0.5</td>
<td>0.1</td>
<td>0.16</td>
</tr>
<tr>
<td>Chimney 16m Width 0.6</td>
<td>calculation</td>
<td>0.6</td>
<td>0.024</td>
<td>0.101</td>
<td>0.29</td>
<td>0.5</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>Chimney 4m Width 0.6m</td>
<td>simulation</td>
<td>3.1</td>
<td>0.016</td>
<td>0.35</td>
<td>8.37</td>
<td>0.6</td>
<td>23.3</td>
<td>1.02</td>
</tr>
<tr>
<td>Chimney 4m Width 0.6m</td>
<td>calculation</td>
<td>4.0</td>
<td>0.016</td>
<td>0.81</td>
<td>13.85</td>
<td>0.6</td>
<td>23.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Chimney 16m Width 0.6m</td>
<td>simulation</td>
<td>3.1</td>
<td>0.016</td>
<td>1.38</td>
<td>8.37</td>
<td>1.5</td>
<td>23.3</td>
<td>1.01</td>
</tr>
<tr>
<td>Chimney 16m Width 0.6m</td>
<td>calculation</td>
<td>3.9</td>
<td>0.016</td>
<td>3.09</td>
<td>13.05</td>
<td>1.5</td>
<td>23.3</td>
<td>0.77</td>
</tr>
<tr>
<td>Chimney 20m, Width 1.0m</td>
<td>simulation</td>
<td>3.3</td>
<td>0.017</td>
<td>2.82</td>
<td>9.24</td>
<td>4.0</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Chimney 20m, Width 1.0m</td>
<td>calculation</td>
<td>2.1</td>
<td>0.018</td>
<td>2.55</td>
<td>3.83</td>
<td>4.0</td>
<td>3.2</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Figure 6.38 results from the simulation model.

In the model the calculations leave high amount of good results out as result of the bypass of the circular calculation. When the sum of wind and stack pressure are positive there should be always a flow as the resistance is dependent on the mean velocity. The \( Q_{N-S} \) is the column that is the final volume calculation.

CFD simulation

As double check a fluid dynamic simulation is done for a simplification of the office. The dimensions of the office are the same as in the design, 4 meters wide, 0.9 meter plenum and an office with 12 occupants. No objects were placed in the office, this can be further
analysed to control flow pattern, per office setting. The simulation uses both cross as stack ventilation. Only variable is the chimney. Difference between two chimneys of 7.5 meters and the design option of 4 single story chimneys.

Amount of hours in HVAC saving is hard to predict with the Design Builder software. The strength in the design is the support of mechanical and concurrent ventilation. This requires other software programs, over which I don’t have the knowledge to run them. Due to comparison of different options, the software can still be used. With the absolute volumetric flow optimizations can be done.

Table 6.14 Design Builder results

<table>
<thead>
<tr>
<th></th>
<th>4 chimneys of 3.5m</th>
<th>2 chimneys of 7.5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.822kW NV cooling (+5.7%)</td>
<td>7.409kW NV cooling</td>
<td></td>
</tr>
<tr>
<td>8.4m² window surface chimney</td>
<td>9m² window surface chimney</td>
<td></td>
</tr>
</tbody>
</table>

Results show similarities. The incoming radiation is a bit higher for the two chimneys, this is probably due to the fact that the 7.5-meter chimney has more window surface. Temperatures are quite the same, and the amount of air changes per hour show small differences. As well is the green line. The natural cooling capacity. Showing a small difference in advance for the 4 single story chimneys (+5.7%). Confirming earlier conclusions about the functionality of the solar chimney in Singapore as stack / wind pressure chimney.

Chimney conclusion

The chimney shows a limitation by the pressure losses caused by high velocities. This can be reduced by increasing the surface area. Surface area is depending on the opening areas in the entree, section and exit. For greater values all three of them should be bigger, not just one as the flow is limited by the smallest section. Length of the chimney increases the friction and delivers a negative result as it ignores the positive wind pressure. The influence of radiation is minimal. If radiation would have been of influence it should show the equality per façade and bigger influence for the width changes.

Table 6.18 Radiation per façade orientation for the design combinations Kwh/m²/year

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>244</td>
<td>427</td>
<td>482</td>
<td>436</td>
<td>252</td>
<td>159</td>
<td>147</td>
<td>162</td>
</tr>
</tbody>
</table>
East-West orientation scores better for all the chimney variables, length, depth and width. This has probably to do with the strong winds from North-South directions that still practice positive influence on East-West facades, and the relative high.

Wind and internal heat are the main drivers up to a certain chimney length, where the pressure losses are equal to the pressure difference and potential hours don’t increase anymore. The single length chimney has the highest potential based on the effective surface area.

**Combination of façade components**

For the combination of the chimney with the wind facade component there are some extra conditions that should be taken into account. For the main achievement to reduce cooling load it can be possible that there is connection between the two components. If wind and solar induced ventilation can reach a comfortable situation together (10% sun +90% wind) it is accounted as comfortable.

With a chimney height the preference of the system is to function without any chimney. This is due the high friction losses in the chimney, and the combination of the façade prefers clearly the North-South direction of the prevailing wind. When combining the
The easy advantage of the “cross ventilation” chimney is not accountable anymore as the results are summed up and thus the easy counts, the hours where it is relatively easy to function fully passive, are done by the cross ventilation.

The strength of in combining the two systems is the possibility to assist the HVAC system with extracting air from the office when outdoor conditions don’t allow this. High temperatures and high humidity.

As it is the task to reduce the mean velocity in the duct, the dimensions are limited by the building. In the analysis of high-rise buildings plenum plus floor space is up to 1.5 meter the dimensions for the duct in the ceiling are 90cm for this thesis.

Segmentation

With chimney height of 20 meters (5 floors) there is space for one chimney for each 5.4 meters of façade. There can be a less high chimney but then compensated by a bigger width. Cutting the height would normally be inefficient, but this relation does not count for Singapore (table 7.7), with its high amount sky cover and thus low radiation.

Table 6.19 Overview of actual hours HVAC saving for different chimney heights and its ratio of façade and chimney width. For all situations the depth of the chimney is 0.8m and the height of the opening of the entree 0.9m and of the exit 0.8m in height, thickness chimney wall is 5cm on each side. (data without pressure losses by openings and discrepancy error)

<table>
<thead>
<tr>
<th>Chimney width (m)</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>250</th>
<th>N-S</th>
<th>W-E</th>
<th>NW-SE</th>
<th>NE-SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>0.11</td>
<td>0.21</td>
<td>0.33</td>
<td>0.52</td>
<td>0.71</td>
<td>0.53</td>
<td>0.85</td>
<td>1.08</td>
<td>1.26</td>
</tr>
<tr>
<td>0.86</td>
<td>0.22</td>
<td>0.4</td>
<td>0.62</td>
<td>0.84</td>
<td>1.62</td>
<td>0.43</td>
<td>0.65</td>
<td>0.86</td>
<td>1.21</td>
</tr>
<tr>
<td>0.76</td>
<td>0.32</td>
<td>0.6</td>
<td>0.82</td>
<td>1.04</td>
<td>1.54</td>
<td>0.48</td>
<td>0.68</td>
<td>1.04</td>
<td>1.54</td>
</tr>
<tr>
<td>0.65</td>
<td>0.42</td>
<td>0.8</td>
<td>1.02</td>
<td>1.24</td>
<td>1.74</td>
<td>1.05</td>
<td>1.51</td>
<td>1.54</td>
<td>2.04</td>
</tr>
<tr>
<td>0.54</td>
<td>0.52</td>
<td>0.9</td>
<td>1.12</td>
<td>1.34</td>
<td>1.84</td>
<td>1.55</td>
<td>2.01</td>
<td>1.54</td>
<td>2.04</td>
</tr>
<tr>
<td>0.32</td>
<td>0.72</td>
<td>1.1</td>
<td>1.34</td>
<td>1.56</td>
<td>2.06</td>
<td>2.14</td>
<td>2.61</td>
<td>2.04</td>
<td>2.54</td>
</tr>
<tr>
<td>0.22</td>
<td>0.86</td>
<td>1.2</td>
<td>1.46</td>
<td>1.68</td>
<td>2.18</td>
<td>2.14</td>
<td>2.61</td>
<td>2.04</td>
<td>2.54</td>
</tr>
<tr>
<td>0.11</td>
<td>0.97</td>
<td>1.3</td>
<td>1.57</td>
<td>1.79</td>
<td>2.3</td>
<td>2.14</td>
<td>2.61</td>
<td>2.04</td>
<td>2.54</td>
</tr>
</tbody>
</table>

*Note: Data with pressure losses by openings and discrepancy error.*
In the Northeast-Southwest orientation and at half width of the wind façade / chimney the results are the best. The surface of the wind component is depending on the width of the chimney. Based on the effective area more square the higher the surface will lower the mean velocity, and thus decrease the resistance. This is in line with the 50/50 ratio for wind and chimney.

All versions show less high results in Northeast-Southwest orientation and at half width of the wind façade / chimney the results are the best. The surface of the wind component is depending on the width of the chimney. Based on the effective area more square the higher the surface will lower the mean velocity, and thus decrease the resistance. This is in line with the 50/50 ratio for wind and chimney.

The relation between height and actual hours without HVAC is caused by friction in the inside of the chimney, where a higher chimney has more surface area and thus more friction. The thickness of the sidelined is of influence. Where for each chimney the thickness of each wall is 5 centimetres (per chimney 10cm). For a five storey high chimney the loss is 50cm in total, and only 10 cm for the single chimney per story.

The performance and orientation, which seems to level if the height of the chimney is reduced, indicates the influence of the prevailing North-south wind direction. Long chimneys are less affected by the wind pressure on the outlet of the chimney. Where the resistance in the chimney is decreasing the efficiency per meter on long chimneys. However, long chimneys are less effective than the shortest ones, costs can be considerable higher with more fans, diffusers etc.

Based on this calculation by mass flow there will be big parts opaque and big parts transparent to enhance the width of the chimney. Meaning that for daylight control, personal flow control, air mixture, shading and view this may be not the best solution.

Where in a high radiation location the results would have been in advance for length of the chimney, in Singapore is visible that single story chimneys produce higher amount of potential hours in HVAC saving. This is line with the prediction that the effective opening area is the important driver for an airflow. Where with the two story chimney the wind façade is cut in two to facilitate space for the chimney of the underlying office. For this reason, the wind façade is not as productive and thus the chimney as well. Since the inlet of the chimney is defined by the effective surface of opening of the wind façade.
One of the limitations is that the flow is limited by the effective surface. It is more efficient to make two separate chimneys.

**Zoning**

Creating a personal airflow requires more control, daylight spreading, and solar shading needs a higher segment frequency, and for the actual flow mixing of air, air needs to be completely mixed. Segmentation showed that the performance can increase due to the wind conditions in Singapore, where the best height for the chimney is one story. For the single story chimney, the six most likely zoning options are shown in table 6.18.

**Table 6.150 Zoning options for single office with single story chimney height.**

---

**Figure 6.41 Curve for single chimney with pressure losses and gains, blue line is sum pressures.**

The variation is within amount of chimneys per façade. Where it is possible to place 1 – n façade segments per office façade. The higher the amount of chimneys the better the shading is, as depth of the chimneys stays the same, 0.9m. However, this will increase operation and installation costs and increases the amount of exterior façade area for maintenance. Selection criteria are as followed, each column representing a priority status, where high-level factors have more influence on the design parameters.
The zoning option with five chimneys scores slightly better than with four or six chimneys. More than six chimneys is possible but due to the extra façade area less favorable and HVAC saving are not higher, therefore not available options.

The HVAC saving values are the highest average score per option. Meaning that the actual performance per orientation and height can be slightly higher. HVAC saving as the highest score is 598 saving hours for East-West orientation with 5 chimneys.

Wind and monsoon loads perform high horizontal loads and more supporting brackets would have been needed if segment width is larger. Big width for window panes require more weight to overcome these horizontal loads, making it for fabrication and transportation less attractive the big width.

Segment width allows installation without big cranes, and with the dimensions limited amount of panels to fill up the façade, making it efficient for installment and less façade area needed than for five chimneys.
The ventilation concept of air mixing can only function if the throw of the airflow is long enough and the extraction equally divided as well. With more vents the flow will be slower but temperature will be more homogenous, and thus better mixing. With less extraction points the change that mixing is not completely done is bigger. Although these are not calculated, with one segment of 5.4 meter, the inlet and outlet have the biggest horizontal distance (table 6.7), and should perform worse in air mixing. In this case the throw of the natural supplied air is not far enough to support the occupants.

For the mechanical support system this has some influence as well. With a bit more spreading the system will mix better. The mechanical support uses the chimney to extract the air. Where round ducts have the highest potential therefore the more square section is desirable.

The amount of spreading of the windows can optimize indoor comfort conditions to maximize occupant’s state of mind. For all the options the ratio wind façade and chimney is 50/50 and window wall ratio 37.5%, thus passing the minimum requirements of 30%.

There is an advantage for the smaller segments in the window spreading on the façade, where low angled radiation is better blocked and glare decreased and thus less discomfort and internal heat gains.

The zoning option with four chimneys is therefore the best option for a high-rise office façade in Singapore based on previous factors. With overall good performance and change for small increase in HVAC saving. This will be the main focus in the optimization as the best combination is option zoning four.

**Conclusion façade performance**

Of the 16 façade monitoring points (orientation and height) the general HVAC saving hours is to be expected between 300 and 700 hours per year (10 – 20%) with RH limit of 80%. The big difference is in calculation method. Initial simulation where higher friction factor is used and the opening resistance is ignored, as with this calculation still had errors, the real value will be higher. A second look gave much lower values where the chimney only could support 2%, and overall values were not higher than 250 hours HVAC saving. In the second attempt all the resistances were counted, but due to the bypass of circular calculation the resistances were too high and even when wind and sun pressures were positive the resistance was bigger than the sum of the positive pressures.

Both calculations show the best performance for higher heights in north-south direction with 50/50 ratio. Where the cross ventilation is more effective, but due to humidity restricted. This is reasonable to be true, as calculations can confirm the relation. As the error is only for stack ventilation, an extra control is done where humidity was no limit and cross ventilation could reach up to over 30% efficiency. The amount of effectiveness
is however depending on a lot of external factors, as heat columns, preferences, personal airflow, humidity and outdoor temperature it is hard to give the exact number with only a static calculation.

6.6. Design optimization

Chimney design

Based on performance it is clear that a single story chimney gives the best performance based on the losses of the mass flow calculation. Though there are some optimization steps that can improve the performance based, without direct relation in efficiency. The single story chimney with four zoning zones is further analyzed to improve control over the performance.

Exit design

A necessary stack length of 3.4 meter this leaves 55cm of opening height before the next chimney start. This leaves the following options for the opening area design. Orange is the available exit area.

*Table 6.21 Exit surface opening possibilities*

<table>
<thead>
<tr>
<th>Type</th>
<th>1. all open sides</th>
<th>2. diagonal</th>
<th>3. curve</th>
<th>4. square opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max chimney length</td>
<td>&gt;3.5m</td>
<td>3.2m</td>
<td>3.3m</td>
<td>3.0</td>
</tr>
<tr>
<td>Max height exit</td>
<td>3x0.55m</td>
<td>0.66m</td>
<td>0.65m</td>
<td>0.55m</td>
</tr>
<tr>
<td>HVAC hrs saving</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Construction</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Fabrication</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Flexibility</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

There is only one option in which the chimney can maintain its performance. Although there is not much loss in relation to the preferred height, extra complexity of the duct increases, flexibility and fabrication process will be more complicated.
It is logical to choose a design solution where all four sides are (partly) open. This will allow rain and animal protection as these have a higher discharge coefficient what can be levelled with a bigger surface area. For the top as the bottom this leaves a relatively simple geometry which is easy to maintain and adapt for each orientation and height preference.

Table 6.22 Ventilation outlet design references

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>New church tower in Delft, Netherlands</td>
<td>Large grills, all sides are open.</td>
</tr>
<tr>
<td>Ventilation inlet for Energon office in Ulm, Germany</td>
<td>Good esthetics, rain and animal protected. All sides are open</td>
</tr>
<tr>
<td>Industrial ventilation outlets</td>
<td>Bad esthetics, rain and animal protected.</td>
</tr>
<tr>
<td>Solar XXI building in Lisbon, Portugal</td>
<td>Small horizontal opening behind PV panels.</td>
</tr>
<tr>
<td>Centre Pompidou in Paris, France</td>
<td>Esthetics and round opening with rain cover.</td>
</tr>
</tbody>
</table>

Mechanical support

The system needs to be supported by a mechanical fan in order to create a continuous thermal comfort. The fan should complement the chimney in extracting the air. Possible positions are showed in the figure. Due to the mirror image design only one side of the building is shown. Position A is in the top of the exhaust, position B is in the ceiling.

Table 6.163 Possible locations for ventilators

<table>
<thead>
<tr>
<th>Option</th>
<th>Option A</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Single fan in chimney part outside</td>
<td>Each zone has its own fan</td>
</tr>
<tr>
<td>Fabrication</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Operating</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Flexibility</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>HVAC saving hours</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maintenance</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>
In case option A is applied there will be 4 fans needed per office. With only four fans there will be less maintenance costs can be reduced. For option B occupants will have a personal fan above their head. This will lead to smaller fans and can be more flexible; in case one side of the office is not used it can be put off (or controlled by sensors) and only opens when temperature is too high etc.

Materialization

Based on the outcome of earlier combinations HVAC saving is done by the internal heat load and not purely by solar radiation. It is important that the duct is good insulated. In Design Builder different chimney compositions have been tested regarding the composition of insulation glazing and glass ratio.

The composition set-up has been a simple chimney with opening on both sides, bottom and top. The flow leaving the chimney in the top is monitored and used as base for table above. The numbers correspond with amount of complete cells above the zero line and thus not the amount of cubic meter per second. Separation is made where the flow is relative greater than other compositions.

<table>
<thead>
<tr>
<th>Composition</th>
<th>25% glass</th>
<th>50% glass</th>
<th>75% glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric flow</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>rating</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Of the three compositions the chimney with 3 insulated sides and double glazing on the front side of the chimney had the highest volumetric flow (25% glazing). This result confirms earlier conclusions about the functioning of a solar chimney in Singapore. Due to the high heat load the stack effect is higher by this heat and the additive heat from the radiation is less attractive. The composition of the black body should be having a high heat capacity and good insulation. XPS can be a good option, where a metal can be suitable black body attached to it.

Reverse stack effect

Next to the fans a second blockade should be implemented to stop the airflow in the chimney in case wind is stronger than the stack effect and reverse chimney effect occurs. Without interference of the other side of the chimney the lock should be in the vertical part and not in the horizontal duct in the building.
Position C doesn’t interfere with the chimney and is in the end of the horizontal duct. The lock will be therefore easier accessible for cleaning. The daylight collector function forms still a problem. Therefore in this situation the lock needs to be transparent as well. There won’t be any direct sunlight as position B, but there still needs to pass as much light as possible.

Option A will be the best in order to combine the function with rain protection and to maintain all installations, ventilator and valves in single segment. To place a certain obstacle in the tip of the chimney. It has to for fill several functions.

Option A will be the best in order to combine the function with rain protection and to maintain all installations, ventilator and valves in single segment. To place a certain obstacle in the tip of the chimney. It has to for fill several functions.

Table 6.175 Reverse stack effect blocking options.

<table>
<thead>
<tr>
<th></th>
<th>Self-closing wind vent</th>
<th>Ventilation damper</th>
<th>Moveable lamellas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure loss</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rain protection</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Fire protection</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>passive</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Rain

The ventilation damper has the advantage to make the duct fire resistant. This has the negative effect that it will have more pressure losses and is not complete passive. Though
the building requirements can require that the building needs fire compartment separation and thus the ventilation damper is obligatory. The best possible position is then at the top to function as rain and reverse stack blockade as well. The self-closing vent is not completely sealed and therefore it may be possible that in combination with rain there still water can enter.

**Cross ventilation design**

**Window openings**

In the wind façade segment there are two vents, monsoon and high vents. And there are two type of operable windows. One for occupant’s personal comfort, and one for the ventilation control. The desired effect of the high windows is to control the flow and to direct the flow away from the occupant’s personal zone by the Coanda effect. In this way the personal space will not have the discomfort, and heat can still be removed by the airflow in the top space in the office.

On the leeward side the window area should be bigger to enable a bigger opening surface. For optimum breeze collection the window design is more important than orientation and thus is it desirable to have the least amount of resistance of the window.

Of the three types of windows (figure 7.1), the pivot window has the least amount of friction and doesn't interfere with the occupant’s personal zone. For this reason the lamella windows have the advantage of guiding the wind without giving it direction, and minimize the resistance, even if they are insulated. This is necessary for the mixed-mode mode when the cooling is working and only limited amount of cold loss should be obtained. Insulated louvres require a frame something that is optimal for transparency, but inevitable.

![Figure 6.44 facade window openings and horizontal flow effect](image)

For the lower window it is preferable to have the maximum view experience and the possibility to open for the psychological advantage it has on the thermal comfort experience.
Figure 6.45 window preferences

It is not desirable to have more lamella windows as these can obstruct view from the working position. Neither should it interfere with other occupants. A standard casement window can be a solution with a double hinge so that it can have two open possibilities. In tilted position it is not having direct flow, Full open it will have a big opening what discomfort creates if occupants are close by. In case the office is almost empty it can create a strong breeze at desk height.

Vent openings

Operable automated dampers have to control the airflow in case there is high humidity and or high temperatures. The dampers have to function continuously and need a rain protection. As these are more technical installations they will have to be selected by the company that will produce the curtain wall system. The resistance needs to be low.

Table 6.26 existing natural ventilation systems of Intelivent with fan support, fire protection and grille

Parapet ventilation opening with damper, double rain protection and grill on the inside. Lowered ceiling for natural ventilation. Ventilator is placed in the duct. Acoustic baffle and fire dampers.
Façade construction

For the structural part of the façade there are several options. But there is the limitation of installation on high-rise buildings. The normal curtain wall façade is build up out of loss segments what makes it preferable to have them in units installed. The unitized curtain wall. Another façade that is made in elements is based on composites. These panels are constructed in moulds thus a less flexible production process. As the chimney is attached to the element it is necessary that the facade has sufficient strength to support the chimney.

Singapore is close to the sea what requires a façade material that is more salt resistance than normal. Another requirement is that the façade is flexible to adapt to each orientation and height, the composite may be less flexible in this case. To have sufficient support for the chimney and allow the openings on a segment of 4 meters height needs sufficient stiffness to prevent bending by the horizontal wind loads. The aluminium curtain wall is a good solution as the details stay the same for every composition. Adaption of the mullions can deliver the needed strength. Therefore, the unitized aluminium curtain is the chosen as it is a well-known system for high-rises.

These wall systems have requirements which include structural load transfer and resistance, water infiltration protection, air infiltration control, condensation prevention, energy management, sound attenuation, safety, maintainability, constructability, durability, aesthetics, and economic viability (Khoraskani, 2015).

Curtain walls and perimeter sealants require maintenance to maximize the service life of the curtain walls. Typical service life of 10 to 15 years for sealants if properly designed and installed, although breaches are likely to occur from day one. Removal and replacement of perimeter sealants requires thorough surface preparation and thus proper detailing.

Aluminium frames are generally painted or anodized. Factory applied fluoropolymer thermoset coatings have good resistance to environmental degradation and require only periodic cleaning. Recoating with an air-dry fluoropolymer coating is possible but requires special surface preparation and is not as durable as the baked-on original coating. Anodized aluminium frames cannot be "re-anodized" in place, but can be cleaned and protected by proprietary clear coatings to improve appearance and durability.
Attachment of the chimney

The integration of the chimney to the façade is essential for the final design and efficiency. As chimney width and wind façade component are dependent on the effective surface area, it is essential that the thickness of the profiles is limited. With a minimal thickness of 25mm for split mullions and 10mm for the dilatation to allow temperature settings the space required is minimum 60mm (Kock, 2016). In this thickness the sandwich panel will be the same thickness as efficiency is defined by the smallest section.

The chimney needs be hanged on the façade to be (cost) efficient during assembly and transportation. The use of standardized profiles is required, but they can be customized in terms of extra fins, slaps or millings. By rotating the profile with the mullion on the outside, a possible cold bridge is introduced. This can be minimized by the thermal separation and the insulation of the bracket.

The main problem is the air tightening of the chimney. This can easily be done with rubber gaskets (green balloon between sandwich and mullion). The chimney can be hanged on the unitized curtain wall panel in different ways.
For the connection a male, female connection needs to be realized somehow. Where milling of the mullion can be done or the mullion can contain a connector what is hanged in the chimney’s sandwich. As the width of the two ‘splitted’ mullions should be minimal, option 3 falls out. A similar design where a fin from the sandwich enters the mullion and is connected via bolts to the main bracket seems to be a good solution. In this way the weight of the chimney is directly transported to the main floor.

In an interview with façade builder Scheldebouw, it seems to be easily done the attachment of the chimney, simple male-female connection should support the weight. Where four points are needed, two top ones to handle the weight, and low connection that allows thermal expansion of the chimney.

**Structural Glazing**

In structural sealant glazing systems, instead of using mechanical elements such as pressure plates and gaskets, the infill glass panels are fixed to a primary frame system using structural silicon sealants during the factory assembly. With structural sealant, there is no need for external metallic elements to put the glazing panels in place and under pressure, it is possible to cover almost the total external surface of the envelope with glazing panels. The units can be completely preassembled in the factory and similar to unitized systems installed directly on the building structure and fastened together or a substructure of mullions and transoms can be assembled on site and later partly fabricated units composed of glazing panels and a border frame can be bolted on or fastened to the substructure.

It is customary to assist the structural sealant patches with some mechanical supports, mainly in the form of resting brackets on the lower frame and withholding the weight of the infill panels. This would reduce the size of the sealant bed and sometimes make it possible to use structural sealant patches only on two sides and leave the rest to non-structural sealants (Khoraskani, 2015).

**Fan support**

Current design has a cross in the chimney to support the ventilation extraction. As it is unknown what the force/vibration of the motor it may be necessary to have a rigid construction to support this. The support will interfere with the airflow and therefore needs to be as slim as possible. As the flow in the chimney absorbs the heat, the expectation is that the temperature difference won’t be...
higher than 10 degrees. For 20 degrees temperature difference the expansion is 0.346mm. As the window will expand as well, this will flatten out the effect and will cause no problems.

\[ \Delta L = \alpha_{material} \cdot L \cdot \Delta T = 17.3 \cdot 1000 \cdot 20 = 0.346 \text{mm} \]

**Table 6.18 Thermal expansion coefficients (source: http://physics.info/expansion/)**

<table>
<thead>
<tr>
<th>material</th>
<th>aluminum</th>
<th>glass</th>
<th>iron</th>
<th>steel, stainless</th>
<th>steel, structural</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha ) (10^{-6}/\text{K})</td>
<td>23.1</td>
<td>8.5</td>
<td>11.8</td>
<td>17.3</td>
<td>12</td>
</tr>
</tbody>
</table>

**Stiffness**

There are several elements that can foresee in rigid U structure. With the structural glazing, the forces can be transported via the window and the strength of the box can be maximized. Together with the chimney floor, the dampers, and the fan, forces from wind can be brought over to the main structure via the pin construction.

Brackets support the principal panel. The steel plate is continued to support the chimney box. In the top there is a fixed connection without any space for errors. The lower support is able to compensate for thermal expansion by the chimney.

The support should be sufficient to give the stiffness and still able to maintain a slim design. As the box is just 1 meter and 4 meters in height the wind load can be brought to the main panel. Between the main panel the vertical connection is done with shear keys.

*Figure 6.50 Wind force brought to the main floor by stiff chimney floor, damper frame and sandwich panel.*
Box in box components

The different functions the façade will get are achieved by subcomponents. These components are made by different suppliers. The chimney is one of the subcomponents, but as well the damper with rain protection, the windows and the aluminium curtain wall frame. The integration of these subcomponents will be a challenge. By defining the different components, the sub-contractors only have to deliver their component box.

Condensation

In case it rains, firstly rain is stopped by the ventilation louvre in the chimney, and no direct rain can enter. High humidity and the extra heat in the leaving air can cause condensation. As in the chimney the temperature is on its maximum the condensation point will be near. This a problem is hard to solve, as the chimney needs to be sealed. Aluminium is capable of dealing with some water, but better would be if there is some kind of drainage system. One that can be activated as moisture is detected. This will influence performance occasionally.
For the thesis project the limitations for wind and buoyancy driven ventilation are tested for a high-rise office in Singapore. The ideal solution would be that with certain adaptations in the façade can cool down the building without the use of any cooling appliance. In this chapter the final design of a high-rise façade that is broadly applicable is shown and demonstrated.
7.1. Final design

Location & orientation

Final performance is depending on the height of the chimney, orientation and floor level height. The maximum chimney height is 3.5 meters for floor to ceiling height of 4 meters, actual performance is based on the local site’s urban canyon.

Facade Functions

With high humidity levels and high temperatures, a fully natural ventilated office is desirable but there should be an alternative to maintain a comfortable work environment at all times and to give the occupants full control over their environment which is in line with the company culture in Singapore. In case of a renovation the building will keep the original HVAC system. The system should run solely on natural ventilation when possible. In case outside temperatures are too high to maintain comfort in the office, if humidity levels are too high the HVAC system will assist in the supply of fresh air.

Functions of façade:

- Enhancing of stack effect and cross ventilation
- Minimize the blocking of the view
- Allows adaptive thermal comfort; operable vents and windows
- External sun blocking; reducing heat load & discomfort glare
- Minimizing energy losses

Facade type

In high rise structures the façade acts as a mediator between outside and inside without having any structural function. The column structure allows the use of large glass areas. A unitized curtain wall system can be applied for easy installation and small components are optimal for easy manufacturing and transportation. Wind driven ventilation should be available when possible, therefore operable windows and vents are implemented with manual overdrive to maintain larger thermal comfort zones.

Design load and occupancy

The occupancy of the office will be accounted for 12 persons. In this case the design will be durable as the occupancy load is relative high with 6.75m²/person (30W/m²).
Design integration

Integration of different functions to create an optimized ventilation/cooling system needs to be designed without delivering a less comfortable environment for the occupants. Maximizing the functionality of the local climate and simple adaptability of the concept for unique situations for altitude and orientation.

Ventilation system requirements

To achieve the functional cooling system that can optimizes the use of natural ventilation when possible the system needs to function on several operators. The humidity level allows wind driven ventilation, but in case the value is too high the system switches to concurrent mixed mode. The system is based on two separate systems. One system is accounts for the supply of fresh air, the other system extracts the air. If one system is not sufficient, the other supports. Depending on the outdoor conditions what system the head system is.

Design Incorporations

The design has its limitations, where it is not possible to account everything in the design. The table below describes the incorporations and not included incorporations.

<table>
<thead>
<tr>
<th>Incorporated</th>
<th>Not incorporated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Heat Island effect</td>
<td>Rain</td>
</tr>
<tr>
<td>Internal heat load 200W/pp</td>
<td>Indoor air quality</td>
</tr>
<tr>
<td>Humidity limit 80%</td>
<td>Urban context; wind, sun, rain</td>
</tr>
<tr>
<td>Office activity</td>
<td>Noise, interior and from exterior</td>
</tr>
<tr>
<td>Outdoor temperature max 10%PPD</td>
<td>Resistance calculated</td>
</tr>
<tr>
<td>Local office culture</td>
<td>Effective flow / personal flow</td>
</tr>
<tr>
<td>Adaptive thermal comfort</td>
<td>Sunshade design, external heat load</td>
</tr>
<tr>
<td>Cooling by airflow</td>
<td>Flexible office hours, late &amp; early working</td>
</tr>
<tr>
<td>Cross and solar chimney ventilated</td>
<td>Other activities than office function</td>
</tr>
<tr>
<td>Mass flow calculated</td>
<td>Single side ventilation</td>
</tr>
<tr>
<td>Building management system</td>
<td>Daylight analysis</td>
</tr>
<tr>
<td>Retrofit &amp; flexibility</td>
<td>Temperature gradient, unknown effect</td>
</tr>
<tr>
<td>Mixed-mode operation</td>
<td>Decentralized dehumidification, façade solution</td>
</tr>
<tr>
<td>Daylight entrance / visual contact</td>
<td>New office buildings</td>
</tr>
<tr>
<td>Reverse stack effect</td>
<td>Turbulence &amp; gusts</td>
</tr>
<tr>
<td>Fans to support NV</td>
<td>Legislation</td>
</tr>
</tbody>
</table>
7.2. Final façade design

Final façade is build up out of façade units of 4 meter by 1.35m.

*Figure 7.1 design drawings*
Design functionality

Flexibility

The segment is build up as unitized curtain wall system and allows flexibility as the details remain the same. Strength calculations should be done based on the worst case scenario. The width of the segment stays the same, but length and width of the chimney are variable with simple changes.

![Diagram showing flexibility within the fixed façade segment](image)

*Figure 7.2 flexibility within the fixed façade segment*

When applied on an office building the shading system has to be applied that horizontal lamellas block the remaining direct solar radiation. These fins are attached to aluminum window frame of the chimney. This zone has sufficient capacity to hang lightweight fins.

![Diagram showing zone capable of carrying extra shading lamellas](image)

*Figure 7.3 Zone that is capable of carrying extra shading lamellas*
Openings

The openings are orientated on opposite sides. Enhancing the Coanda effect to generate a flow attached to the ceiling. This is done by the louvre high windows.

*Figure 7.4 Flow pattern. High velocity changes into steady flow. Bigger outlet opening than inlet, where the discomfort for occupants is minimal.*

*Figure 7.5 Occupants are not bothered by the flow*
UNITIZED CURTAIN WALL

UNITED ARRIVE AT BUILDING SITE

The chimney is attached at the building site if possible. Otherwise a depot will be located close to the site for building materials to storage. The elements stand up vertically.

INSTALLMENT

The elements are transported via the lift shaft up to floor above the installment place. The panels contain holes in the shear keys what is used for lifting. The panel can be controlled with suction pads on the glass.

SUPPORT

The BRACKETS are 1.35m from each other, making the system still feasible for construction and there is no extra support needed. The brackets are placed on the structural floor and covered with the finishing floor. This will allow easy installation, placing them as well as adjusting them to their final position.

Vertical connection elements is done with SHEAR KEYS. These reduce the deflection in the façade and unitize the vertically.

FINISHING UP

When the façade is installed and set. inside finishes can be added. Ventilation shafts connected, and the sound and fire proof barrier between floors.
A close look at the joint of two unitized units and the connection with the chimney. A small isolator between the sandwich and the mullion makes the connection airtight. The rubber flipper is there to keep all the rain and dust out. Sealing of the façade is done with the rubber on the inside of the façade. The damper is visible on the right with the mechanism that enables the closure of the louvre vents. In front of that the horizontal lamellas are there to keep rain out.
Horizontal joint unitized wall segments and chimney, scale: 1:5, (at one meter)

The detail shows the section with the maintenance door for the chimney and the operable window.
The structural glued double glazing of the chimney. 6mm silicon kit between glas and the aluminium sandwich panel. On both side of the XPS aluminum is placed (1.5mm sheet). On the inside this will be black to increase the solar absorption. The side panels can be in the desired colour of the architect. White will be the best for the sides as this has the highest reflection factor and least heat is absorbed.
Vertical section Façade 1:20

Section Façade 1:50 (not in scale anymore)
8. REFLECTION
8.1 Discussion

The potential for wind and stack ventilation in the tropical climate of Singapore doesn’t say anything about human thermal comfort. Although the application of the adaptive thermal comfort model of De Dear indicates that it is allowed to have 10% people dissatisfied, it is not adapting to deal with the local office culture in Singapore.

It is therefore hard to judge if thermal comfort is maintained. To react on the local office culture the limit of 80% relative humidity is applied, with this limit there is proven to be not that much of affection due to humidity and thus the normal rules can be applied. This does however influence the design and limits the hours of possible natural ventilation.

The performance of the natural ventilation is hard to judge, as it is influenced by the amount of hours cross ventilation can be applied, and the effectiveness of the chimney. Vertical temperature gradient is an unknown factor what can reduce the effectiveness as heat columns can preheat the air at inlet side. Cross ventilation is more effective as less pressure losses are on its path and the wind is sufficient available in the environment of Singapore. The final façade should be based on the ratio cross-ventilation and chimney effectiveness, where both optimums are with highest possible effective surface area.

In the simulation model the combined effects of cross and stack were able to manage 16%. This is however with several errors and the simplification of pressure losses. In a more advanced simulation the values seem to be much lower (7% HVAC saving hours), but in this case the pressure losses were based on initial speed. The final performance seems to be somewhere around 10 – 20% without any temperature change of the inlet by temperature gradient and heat columns. As this is based on average data, the constant changing environment and the possibility of occupants to disturb the settings of the building management can further decrease the efficiency.

Table 8.1 HVAC saving hours based on 10%PPD for final compositions. Height and orientation are variable to know the saving potential for existing buildings, but contains errors.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Chimney/WAC</th>
<th>WAC</th>
<th>VR-WAC</th>
<th>VR-WAC/LR</th>
<th>VR-WAC/DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 8.1 HVAC saving hours based on 10%PPD for final compositions. Height and orientation are variable to know the saving potential for existing buildings, but contains errors.
Figure 8.1 the error of the second simulation where positive pressures result is no flow, something that is impossible and thus results should be much higher, than the 6% by this simulation.

The 10 – 20% seems plausible as the environment is windy and thus a large volume replacement can be possible. The 43% from earlier research is hard to reach for office environments, as these function during the day when normally rain occurs and thus high humidity levels.

The flow in the chimney is still uncontrollable, with high speed and high friction, and the low preferred height. Where in the beginning the height of the chimney was a driver, finally after applying the pressure losses the design completely changed. These continuously adapting to errors are part of the learning process, and can still find improvements.

Therefore, the decision was made to insulate the chimney, where stack pressure combined with wind drives the chimney and radiation plays a little role. The height of the chimney is limited, something what was not suspected on forehand. Where the initial concept consists of a 5 story high chimney after reading about the Commerzbank in Frankfurt, changed into a chimney of 3.4 meter. CFD simulation indicated the same preference to four chimneys of 3.5 over two of 7.5 meter (+5.7%). With the lack of examples and the actual possibility that it can be that due to the small surface area and high internal load the friction is more than the effect it gets from extra length.

Table 8.2 Design Builder results for single office

<table>
<thead>
<tr>
<th>Chimney Type</th>
<th>NV Cooling (kW)</th>
<th>NV Heating (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 chimneys of 3.5m</td>
<td>7.822 kW</td>
<td>7.016 kW</td>
</tr>
<tr>
<td>2 chimneys of 7.5m</td>
<td>7.409 kW</td>
<td>7.016 kW</td>
</tr>
</tbody>
</table>
The calculation model is based on full mixing of air. Depending on the outside temperature the possible temperature raise defines the amount of air needed to remove the heat. The flow is then reduced by primary and secondary pressure losses and have to be compensated in order to remove the necessary volume of ‘warm’ air.

The assumption that the air is mixed is maybe not correct. If air flows from the window to the inlet of the chimney, the distance is shorter, than from the monsoon vent to the inlet of the chimney. The use of diffusers with valves is necessary to truly control the flow and the temperature, what will lead to more losses and thus lower performance. If this is not possible then the danger is there that the room will heat up, something what should be prevented at all time as this can dramatically reduce the amount of possible HVAC saving hours.

Besides the airflow is calculated based on mean pressure difference alone and fluctuating pressure effects are ignored. For low wind speeds, fluctuating pressures can cause airflow greater than that would be predicted by the procedures.

For cross-ventilation the discharge coefficient that I applied on the volume flow to simulate the friction of the office of 0.27 (0.65^3) can be one of the factors that influences the actual saving. It is unknown what the flow inside an office will do. It definitely will reduce speed, but if it actual discharges the flow for 70% is unknown, and can be further investigated for the actual HVAC saving hours.

The combination of the stack ventilation and cross-ventilation has been a good solution. Something that I didn’t expected to be this helpful. Where for both separated the values not even reached up to 11%. It can be that the assumed values for the calculation of the HVAC saving hours are a bit too high, but still that with a simple façade design a potential saving up to 20% can be made is an indication that there is space for energy savings on the cooling loads in tropical high-rises.

The HVAC saving hours per year produced the final dimensions for the design. By using the amount of HVAC saving hours it doesn’t imply what kind of hours. In practice the easy hours where outdoor conditions allow are used, and the hours when the mixed ventilation is used are ignored. It can be that 1 hour of intensive cooling incorporates more energy than slightly cooling demand for 2 hours or more. In this case the system is not more efficient and thus slightly different outcome is there. For actual maximum cooling load reduction per year the amount of energy used by other systems should be implemented in the calculation.

Floor to ceiling height is limited and therefore light can’t penetrate as far as possible. This will lead to more artificial lighting and therefore less efficient. Next to this is the height required for the duct for the high vent and the chimney uses a lot of space. This is space that cannot be rented or could be of use to reduce the floor to floor height. Next to this
the final design is extra complicated as there is almost no space for the centralized supply. The idea of redesigning the ducts, that they are smaller in the middle. This is possible because the air is collected or supplied over the full length of the duct. Half way the duct it is just half the volume and this can mean that the duct can be reduced.

Figure 8.3 possible duct height reduction

Another option is to combine the solar chimney with a solar collector that can help in further reducing the energy usage of high-rise offices or by installing photovoltaics in the glass that can generate electricity and at the same time can radiate heat from the back. This will change the flow in the chimney as the glass will get warmer than before. On the one hand will this lead to bigger heat losses, on the other side the air may get a more equal heat spreading as the glass acts as heat absorber like the wall.

Table 8.1 Design concerns

<table>
<thead>
<tr>
<th>Concern</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-displacement</td>
<td>Simple lowered ceiling, sufficient effect?</td>
</tr>
<tr>
<td>Resistance of duct</td>
<td>Is the resistance low enough to allow NV?</td>
</tr>
<tr>
<td>Moisture and rain</td>
<td>How is dealt with rain or moist inside the duct</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Maintenance of outside facade</td>
</tr>
<tr>
<td>Operable windows</td>
<td>Airflow generated by the opening of the window</td>
</tr>
<tr>
<td>Separate zones</td>
<td>To have isolated offices, that can be addressed individually, will this work better?</td>
</tr>
<tr>
<td>MM-mode</td>
<td>In case the façade is closed, is it still the concurrent mm strategy that can be applied or should the HVAC apply the rules of AC mode then?</td>
</tr>
<tr>
<td>Local office culture</td>
<td>Will they accept NV and the 80% RH level</td>
</tr>
<tr>
<td>Accumulation of heat</td>
<td>Overheating in NV mode?</td>
</tr>
<tr>
<td>Formula used to calculate the saving</td>
<td>Not good insight with 1, ½, ¼ of the actual saving.</td>
</tr>
<tr>
<td>Effectiveness of chimney for NV</td>
<td>Decreasing length increases hours without HVAC, this should be until a certain height.</td>
</tr>
<tr>
<td>Height of the chimney</td>
<td>Maximum preferred length 3.4m</td>
</tr>
<tr>
<td>Local resistances</td>
<td>Too high? Too low, needs testing</td>
</tr>
<tr>
<td>Heat columns</td>
<td>Heat flows in front of the façade can lower the efficiency.</td>
</tr>
</tbody>
</table>
8.2. Conclusion

A reduction of the cooling load can be done via the application of natural ventilation strategies in Singapore if the adaptive thermal comfort is used and air is able to mix. The combination of stack and cross ventilation works complementary, when there is wind cross ventilation, if there is high humidity stack ventilation can still be used with a central supply of air. The combination of partly wind and partly stack saves extra mechanical hours. This makes the combined system more effective than just cross or only a double façade to enhance stack ventilation.

Climate performance; Final design is expected to have performance between 10 – 20% cooling load reduction with the allowance of the 10% dissatisfied people. North-South orientation has the highest potential as that is the prevailing wind directions. As calculations are based on the mass flow, air mixing and extracting may give a different outcome. Height is of influence, as wind increases and expectation is that there will more radiation at altitude as surrounding buildings have less shading effect. The influence of heat columns and temperature gradient can influence results.

Continuous changing, temperature, flux, wind, pressure differences, friction and humidity makes it hard to have control over the complete system. Something that might have been underestimated in the design of the façade, but is partly incorporated in the high resistance factor for the office. For the chimney this leaves high uncertainty.

High velocity (up to 12m/s, delta T 6 degrees) in the chimney generated by wind and internal heat create high friction and thus less tall chimneys are desired to overcome the primary pressure losses. A stack chimney is therefore more suitable in the situation with high amount of occupants and relative small chimney sections; this increases the surface area and thus wind pressures are more beneficial. For less dense offices the ‘solar’ chimney will be more functional with less dependency on large volumetric flow.

The effective surface area is defining the volume of the flow, for cross ventilation this means that the size of the windows has direct relation with the efficiency. For the stack effect the height of the plenum is defining the capacity, as the depth of the chimney, and the opening size can increase up to structural limitations. As high-rises are improving space efficiency, this can cause a thread for future buildings where the plenum height is decreased, this will directly affect the cooling load reduction.

Façade performance; Flexibility in the façade design enables an optimization for each façade and altitude within the same unitized façade component. Small adaptions of chimney width, horizontal shading devices can easily adapt to the urban context. This suits the design requirement for broad application where rehabilitation of existing office building stock towards a more sustainable and less reliance on electrical grid. Where
occupants can remain comfortable during a power failure, without using a backup cooling system.

It is not common in the façade industry to change facades on high-rise structures. A monotone design is standard. For cooling load reduction, future buildings need to have this flexibility to adapt to the urban context. A financial review can indicate the extra costs and the return in cooling savings.

Last word; The building trend in Germany where buildings demonstrate that mixed mode operation is possible for offices has a positive effect in the tropical environment of Singapore as well. The application to the real urban area requires still further development, where the influence of the urban canyon on façade and climate design is hard to predict. However, with a stack chimney radiation is of less influence what can suggest that natural ventilation is possible, a side from the air quality, to apply in high-rise offices in urban dense cities where there is less radiation available.

8.3. Research Questions

This paragraph describes the research questions stated in the beginning with the final findings.

- What is the air INTAKE and OUTTAKE?

The air intake and outtake is defined by the demand and the supply. Where the demand is formed by difference between the comfort temperature and the outside air temperature. The supply is derived by wind and stack pressures and their

- What is the influence of SOLAR SHADING on the natural ventilation?

The main function of solar shading is the reduction in the demand. With less radiation inside the office the temperature difference is bigger, and thus the demand volume smaller. It is this that increases the efficiency dramatically.

- What is the influence of a FLOORPLAN to the façade?

The floorplan has different influences. Firstly, the amount of occupants per façade ratio. The supply of air is depending on the façade surface. As there is a limited amount of façade, where for more economical high-rises the floor to floor height is even less, the collecting of natural resources is restricted. Increasing the density of occupants will require a higher demand, but the supply stays similar (only increase of internal heat load).
Secondly, the floorplan width is essential for the effectiveness of natural ventilation. Floorplans wider than 15 meter are less effective. More obstructions and occupants will be on its path, decreasing the pressure differences between leeward and windward side.

- What is the influence of PERSONAL COMFORT on façade design?

The influence of personal comfort can improve efficiency if occupants allow an airflow close to their body that improves the evaporative cooling. This effect can only be generated by an airflow close from the source, a suction effect will be less or not effective. In current office buildings with only a lowered ceiling it is hard to realize a personal airflow. With new structures, the displacement ventilation strategy can be combined with this local cooling effect. If the floor is high

To create a certain framework, sub-questions need to be dealt with to engage the general research question.

- What are the different options for NATURAL VENTILATION PRINCIPLES for tall office buildings in a tropical climate using the building skin?

The different options that can be applied are, cross ventilation and stack effect. Single sided ventilation has little effect and therefore can only be used in limited amount of time. For the stack effect to be effective high surface area is needed, and solutions with hollow cores are more effective than to put it in a façade solution. As humidity is one of the biggest challenges, the combination of two systems can be a good solution. Cross ventilation when possible and a separate chimney/hollow core solution when humidity levels are too high.

- What are the indoor temperature limits for a natural ventilated tall office building in a tropical climate based on the ADAPTIVE COMFORT MODEL?

With an objective approach the comfort temperature can be described in where 10% of the occupants are dissatisfied. This is the same amount as for regular HVAC system settings. Comfort temperature

- What WIND SPEEDS are acceptable in a tropical office building without having any DISCOMFORT?

Discomfort is caused by draught; this only occurs when people think the flow is too high. In tropical climates airflow up to 3m/s is still comfortable. For offices the limit is based on airflow in the working space. When papers start flying this is seen as discomfort, usually this is around 1.5 m/s; a cooling effect of 2 degrees.

- What are the WIND SPEEDS at 90 to 100m, and higher?
The wind profile shows the increasing speed.

- What is the influence of HUMIDITY on thermal comfort?

There is no direct relation between humidity and thermal comfort. High humidity has influence on the comfort range.

The general research question:

“How can we design a building skin to maintain a thermal comfortable office with wind and stack ventilation in a tall office building in a tropical climate to reduce the cooling load?”

The application of stack in combination with cross ventilation leads to a cooling load reducing building skin. The effect of the chimney as single object is disputable as performance is difficult to calculate, but in combination with the high humidity it is a good solution as extracting device what can deliver shading of the façade surfaces. With the limited amount of façade surface it is better to design wind optimized chimney’s as radiation is low and can be blocked in dense urban areas. Due to changing environment by height, there should be change in ratio over the façade according to orientation, urban context and wind flows. Testing of the façade concept can give clarity about unknown causes for temperature and induced flow by the wind wings.

8.4.  Recommendation

Further improvements can be done with decentralized dehumidification system in combination with a radiant cooling system. Creating a decentralized supply concept of “dryer” air and locally cooled surfaces cooled ceiling the ventilation rate can be minimized and thus the effect of a single breeze will have a bigger impact. During high temperature peaks the building can work in closed mode where the radiant cooling provides the cooling, the humidity level and the ventilation are controlled in the façade. A passive dehumidification system would improve the efficiency, outside air above RH80% can than still be used to for cross ventilation.

Displacement ventilation can improve the heat capacity of incoming air. With displacement ventilation the air will be displaced and thus not mix. This will allow a comfort temperature up to someone’s head during work. Above that the air can be warmer and thus more energy can be saved. An airflow from a raised floor can be an option if the room height is sufficient. The extraction duct has to be in the ceiling as the buoyancy effect creates stack effect. This can be optimized with a local personal airflow that improves the comfort temperature.
Displacement ventilation should be included in the design for new high-rises, as well as the external shading to improve daylight comfort and reduction of the internal heat load. Where the bioclimatic approach should give inside in the core position, openings and zoning for an efficient passive design, that later in the design process can be upgraded with some form of mechanical support in case natural ventilation is not sufficient.

Depending on location, function and outdoor conditions the ratio of stack and cross ventilation can be made. Where the segment width should be based on efficiency, shading, and structure. Depending on the amount of radiation, floor to floor height and occupancy to use a standard solar chimney or with options as light collector and photovoltaics.

The HVAC saving potential approach in combination with yearly calculation is a good approach where modifications are done by the total added value, and not only for unique conditions. In combination with a financial approach this system can present a more valuable for the owner of the building.

Excel doesn’t have the ability to organize formulas with certain hierarchy, this causing some uncertainty about the outcome. Further development of the model, where yearly data is transformed into saving potential percentages should be done in other calculation programs like Mathlab.

### Table 8.2 Design opportunities

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible façade chimney ratio</td>
<td>With aluminum the details stay the same, easy adaptable.</td>
</tr>
<tr>
<td>Daylight savings</td>
<td>Integration of daylight collector in chimney</td>
</tr>
<tr>
<td>Energy productivity</td>
<td>Putting PV’s on the chimney</td>
</tr>
<tr>
<td>Private offices</td>
<td>Via the ceiling the system can still provide natural ventilation via the ceiling and or hollow walls</td>
</tr>
<tr>
<td>Displacement air strategy</td>
<td>If possible the supply of air via the floor to enhance personal controlled airflow, will increase comfort temperature</td>
</tr>
<tr>
<td>City canyon</td>
<td>The façade has potential to function in dense city as the driver is wind.</td>
</tr>
<tr>
<td>Cooling load savings by shading</td>
<td>Further cooling load reduction can be calculated via the radiation reduction.</td>
</tr>
<tr>
<td>Year based efficiency calculation</td>
<td>The saving potential based on yearly data can improve decision, as not only extreme conditions are incorporated.</td>
</tr>
</tbody>
</table>
8.5. Further research

The final product lacks the correct input form the yearly simulation. The simulation model tends to be essential in the development of high-rise facades and the natural ventilation potential, especially for the ratio wind and stack area in the façade. There are several unknown topics that need more research to be able to make a useful prediction of the cooling load reduction. Following points have caught my attention during the making of this thesis. There is no hierarchy between the topics.

- Behavior of induced stack effect in combination with:
  - Clouds
  - Dense urban context, radiation losses.
  - Friction: Primary pressure losses
- Behavior of wind in dense urban areas on high-rise facades.
- Influence of open windows on the pressure coefficient. If all the windows are open the effectiveness will reduce due to the lower pressure differences between leeward and windward side.
- Improvement of basic daylight collector with lenses.
- Improvement of local airflow.
- The temperature gradient: temperature at higher levels in dense urban areas in different climates, seasons, humidity levels and temperatures, diurnal differences. In interviews with people from Scheldebouw I have asked about this effect, they only knew that there is the possibility of heat columns. Therefore, this is one of the key factors for future development in high-rises for dense urban areas.
- Resistance in the solar chimney and wind duct (fluid dynamics).
  - In (Hazim B Awbi, 1994) the friction factor is calculated with an extra factor 4. In previous versions of this thesis I have used this factor. Other literatures don’t imply this factor. The strange thing about factor 4, is that this should indicate the friction per side in the duct, but all ducts are translated towards hydraulic diameters and thus a $\pi$ should have been used by Awbi. As this factor 4 leaves still some questions further analysis of the translation of the friction towards the side walls of the duct should be done.
- Personalized air supply designed in furniture to enhance airflow close to the body.
- The integration of a dehumidifying system and the natural ventilation potential. For instance this graduation design in combination with the thesis design of Melissa Krisanti Tanuharja’s “Integrated Facade System in High Rise Office Buildings in Tropical Climate Condition”.
- Zoning of the offices. Can the chimneys of one office assist the other office.
II. APPENDIX

A. Climate
B. Thermal Comfort
C. Natural ventilation
D. Design
E. Reference projects
F. Extra
G. Curriculum Vitae
Appendix A. Climate

1. District cooling

Chiller plant efficiency has become a key area for initiatives to improve the energy efficiency of commercial buildings in Singapore. Compared to in-building independent chiller plants, a district cooling system is superior in terms of asset efficiency, energy efficiency and service level.

District cooling is an outsourcing alternative to in building chilled water production for air-conditioning. It is well suited for commercial districts with high cooling load density. It raises the energy efficiency related to air-conditioning more effectively on a global scale (Kee, 2010). It improves the building energy efficiency on system scale, but doesn't improve the actual energy consumption by the occupants.

Climate classification

Table 8.4 Description of Köppen climate symbols and defining criteria. (Peel et al., 2007)

<table>
<thead>
<tr>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>Description</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>f</td>
<td>Tropical</td>
<td>T_{cold} \geq 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m</td>
<td>Rainforest</td>
<td>P_{dry} \geq 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w</td>
<td>Monsoon</td>
<td>Not (Af) &amp; P_{dry} \geq 100 \cdot \text{MAP}/25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w</td>
<td>Savannah</td>
<td>Not (Af) &amp; P_{dry} \geq 100 \cdot \text{MAP}/25</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>W</td>
<td>Arid</td>
<td>MAP \leq 10 \cdot P_{threshold}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>Desert</td>
<td>MAP \leq 5 \cdot P_{threshold}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>k</td>
<td>Steppe</td>
<td>MAP \leq 5 \cdot P_{threshold}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>h</td>
<td>Hot</td>
<td>MAT \geq 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>k</td>
<td>Cold</td>
<td>MAT \leq 18</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>B</td>
<td>Temperate</td>
<td>T_{hot} \geq 10 &amp; 0 &lt; T_{cold} &lt; 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td>Dry Summer</td>
<td>P_{dry} &lt; 40 &amp; P_{dry} &lt; P_{wet}/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w</td>
<td>Dry Winter</td>
<td>P_{wet} &lt; P_{wet}/10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>f</td>
<td>Without dry season</td>
<td>Not (Cf) or (Cw)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>Hot Summer</td>
<td>T_{hot} \geq 22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>Warm Summer</td>
<td>Not (a) &amp; T_{mon10} \geq 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e</td>
<td>Cold Summer</td>
<td>Not (a or b) &amp; 1 \leq T_{mon10} &lt; 4</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>s</td>
<td>Cold</td>
<td>T_{hot} \geq 10 &amp; T_{cold} \leq 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w</td>
<td>Dry Summer</td>
<td>P_{dry} &lt; 40 &amp; P_{dry} &lt; P_{wet}/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>f</td>
<td>Dry Winter</td>
<td>P_{wet} &lt; P_{wet}/10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>Without dry season</td>
<td>Not (Df) or (Dw)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>Hot Summer</td>
<td>T_{hot} \geq 22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>Warm Summer</td>
<td>Not (a) &amp; T_{mon10} \geq 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d</td>
<td>Cold Summer</td>
<td>Not (a, b or d)</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td>s</td>
<td>Very Cold Winter</td>
<td>Not (a or b) &amp; T_{cold} &lt; -38</td>
</tr>
<tr>
<td>T</td>
<td></td>
<td>T</td>
<td>Tundra</td>
<td>T_{hot} &gt; 0</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>F</td>
<td>Frost</td>
<td>T_{hot} \leq 0</td>
</tr>
</tbody>
</table>

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{wet} = precipitation of the wettest month in winter, P_{wet} = precipitation of the wettest month in summer, P_{wet} = precipitation of the wettest month in winter; P_{threshold} = varies according to the following rules (if 70% of MAP occurs in winter then P_{threshold} = 2 \times \text{MAT}, if 70% of MAP occurs in summer then P_{threshold} = 2 \times \text{MAT} + 28, otherwise P_{threshold} = 2 \times \text{MAT} + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.
Appendix B. Thermal comfort

1. Thermal sensation

Human Thermoregulation

The human body continuously produces heat by its metabolic processes. The heat output of an average body is often taken as 100W, but it can vary from about 70W (in sleep) to over 700W in heavy work or vigorous activity (e.g. playing squash). This heat must be dissipated to the environment, or else the body temperature will increase. This deep body temperature is normally about 37°C, whilst the skin temperature can vary between 31 and 34°C (Szokolay, 2014). If the heat leaving the occupant is greater than the heat entering the occupant, the thermal perception is “cold.” If the heat entering the occupant is greater than the heat leaving the occupant, the thermal perception is “warm” or “hot”.

Warm conditions

To warm conditions the body responds by vasodilation: subcutaneous blood vessels expand and blood flow increase in the skin, increasing the skin temperature, which in turn increases heat dissipation. In this cannot restore thermal equilibrium, the sweat glands are activated, the evaporative cooling mechanism will operate. Sweat can be produced for short periods at a rate of 4 L/h, but the mechanism is fatigable. Sustainable rate is about 1 L/h. Evaporation is an endothermic process and thus absorbs heat at the rate of some 2.4 MJ/L (=666Wh/L).

When these mechanisms cannot restore balance conditions, inevitable body heating, hyperthermia will occur. When the deep body temperature reaches about 40°C, heat stroke may develop. This is a circulatory failure (venous return to the heart is reduced) leading to fainting. Early symptoms are: fatigue, headache, dizziness when standing, loss of appetite, nausea, vomiting, shortness of breath, flushing of face and neck, rapid pulse rate (up to 150/min), glazed eyes, as well as mental disturbances, such as poor judgment, apathy or irritability.

At heat stroke the temperature rapidly rises to over 41°C, sweating stops, coma sets in and death is imminent. Even if a person is saved at this point, the brain may have suffered irreparable damage. At about 42°C death would probably occur.

Cold conditions

In cold conditions the first response is vasoconstriction, reducing blood circulation to the skin, lowering of skin temperature, reducing the heat dissipation rate. The erection of hair may appear, which would make the fur a better thermal insulator. If this is
insufficient, **thermogenesis** will take place. The muscular tension of shivering, increasing metabolic heat production.

**Shivering** can increase the heat production by ten times. The deep-body tissues remain at the normal 37°C. Body extremities, fingers, toes, ear lobes may be starved of blood and may reach temperatures below 20°C, or in severe exposure may even freeze, before deep body temperature would be affected.

If these physiological adjustments fail to restore thermal equilibrium **hypothermia** will occur, the cooling of the body. The deep body temperature may drop to below 35°C. Death usually occurs between 25 and 30°C. Even if hypothermia is not reached, continued exposure to cold conditions can cause mental disturbances (insufficient blood supply to the brain): willpower is “softened” and conscious control gives way to hallucinations, drowsiness and stupor.

**Table 8.3 Critical body temperatures (Auliciems & Szokolay, 2007)**

<table>
<thead>
<tr>
<th>Skin temperature</th>
<th>Deep body temperature</th>
<th>Regulatory zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>45°C</td>
<td>42°C</td>
</tr>
<tr>
<td></td>
<td>40°C</td>
<td>40°C</td>
</tr>
<tr>
<td></td>
<td>31-34°C</td>
<td>37°C</td>
</tr>
<tr>
<td></td>
<td>10°C</td>
<td>25°C</td>
</tr>
</tbody>
</table>

The table summarizes the critical body temperatures. The skin temperature should always be lower than the deep body temperature. And the environment should be below the skin temperature to allow heat dissipation. The environmental conditions which allow this would ensure a sense of physical well-being and may be judged as comfortable.

**Dew point**

Another indicator for humidity is dew point temperature. The dew point is the temperature to which the air would have to be cooled to become saturated. Below the dew point, water will condense out of the air onto surfaces. In the early morning, grass surfaces will be coated with water if the nighttime temperature has dropped below the dew point. When humidity is high, the dew point temperature is only a few degrees below, or equal to, air temperature.
Clo values

Table 8.4 Garment insulation values. (ASHRAE, 2013)

<table>
<thead>
<tr>
<th>Garment Description*</th>
<th>(I_{\text{clo}}), clo(^b)</th>
<th>Garment Description*</th>
<th>(I_{\text{clo}}), clo(^b)</th>
<th>Garment Description*</th>
<th>(I_{\text{clo}}), clo(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Underwear</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men’s briefs</td>
<td>0.04</td>
<td>Long-sleeved, flannel shirt</td>
<td>0.34</td>
<td>Long-sleeved (thin)</td>
<td>0.25</td>
</tr>
<tr>
<td>Panties</td>
<td>0.03</td>
<td>Short-sleeved, knit sport shirt</td>
<td>0.17</td>
<td>Long-sleeved (thick)</td>
<td>0.36</td>
</tr>
<tr>
<td>Bra</td>
<td>0.01</td>
<td>Long-sleeved, sweat shirt</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T-shirt</strong></td>
<td>0.08</td>
<td>Trousers and Coveralls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full slip</td>
<td>0.16</td>
<td>Skirt (thin)</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Half slip</td>
<td>0.14</td>
<td>Skirt (thick)</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long underwear top</td>
<td>0.20</td>
<td>Walking shorts</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long underwear bottoms</td>
<td>0.15</td>
<td>Long-sleeved shirt dress (thin)</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Footwear</strong></td>
<td></td>
<td>Straight trousers (thin)</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle-length athletic socks</td>
<td>0.02</td>
<td>Short-sleeved shirt dress (thin)</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calf-length socks</td>
<td>0.03</td>
<td>Straight trousers (thick)</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee socks (thick)</td>
<td>0.06</td>
<td>Overall</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panty hose</td>
<td>0.02</td>
<td>Sleeveless, scoop neck (thin)</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandals/Thongs</td>
<td>0.02</td>
<td>Overall</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slippers (quilted, pile-lined)</td>
<td>0.03</td>
<td>Overall</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boots</td>
<td>0.10</td>
<td>Overall</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shirts and Blouses</strong></td>
<td></td>
<td>Sleeveless vest (thick)</td>
<td>0.10</td>
<td>Short-sleeved pajamas (thin)</td>
<td>0.22</td>
</tr>
<tr>
<td>Sleeveless, scoop-neck blouse</td>
<td>0.12</td>
<td>Sleeveless vest (thick)</td>
<td>0.17</td>
<td>Short-sleeved parka (thin)</td>
<td>0.42</td>
</tr>
<tr>
<td>Short-sleeved, dress shirt</td>
<td>0.19</td>
<td>Sleeveless vest (thick)</td>
<td>0.10</td>
<td>Short-sleeved parka (thin)</td>
<td>0.42</td>
</tr>
<tr>
<td>Long-sleeved, dress shirt</td>
<td>0.22</td>
<td>Sleeveless vest (thick)</td>
<td>0.15</td>
<td>Short-sleeved parka (thin)</td>
<td>0.42</td>
</tr>
</tbody>
</table>

*This:* garments are summerweight; “thick” garments are winterweight.
*Clo:* 0.885\(^*\) \(\text{W/m}^2\)\(^\circ\text{C}\)

Predicted mean vote

The result relates the size thermal comfort factors to each other through heat balance principles. To calculate PMV:

\[
\text{PMV} = [0.303e^{-0.036M} + 0.028][(M - W) - 3.96E^{-8}f_{cl}(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}h_c(t_{cl}-t_a) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173 \cdot M(5.87 - p_a) - 0.0014 \cdot M(34 - t_a)]
\]

Where,

\[
f_{cl} = \frac{1.0 + 0.2I_{cl}}{1.05 + 0.1I_{cl}}
\]

\[
h_c = 12.1(V)^{\frac{1}{2}}
\]

\[
t_{cl} = 35.7 - 0.0275(M - W)
\] - \(R_{cl}(M - W)\]
- 3.05[5.73
- 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)]

\(e\): Euler’s number (2.718)
\(f_{cl}\): Clothing factor
\(h_c\): Convective heat transfer coefficient
\(I_{cl}\): Clothing insulation [clo]
\(M\): Metabolic rate [W/m\(^2\)]
\(p_a\): Vapor pressure of air [kPa]
\(R_{cl}\): Clothing thermal insulation
\(t_a\): Air temperature [°C]
\(t_{cl}\): Surface temperature of clothing [°C]
\(t_r\): Mean radiant temperature [°C]
\(V\): Air velocity [m/s]
\(W\): External work (assumed = 0)
\[ R_{ct} = 0.155 l_{ct} \]

PPD is a function of PMV, it can be defined as:

\[ PPD = 100 - 95e^{-\left(0.3353PMV^4 + 0.2179PMV^2\right)} \]

2. Thermal comfort indexes

ISO 7730

The international Standards Organization, ISO, is based on the predicted mean vote of Fanger.

ANSI/ASHRAE 55

The American Society of Heating Refrigeration and Air conditioning Engineers (ASHRAE) standard 55 (2004), is the standard that able to define the range of indoor environmental conditions that are acceptable in order to achieve the thermal comfort for occupants. This standard uses the relationship between the indoor comfort temperature and the outdoor temperature to define the permissible zones for the indoor temperature in naturally conditioned building. In 2010 a revision was made and together with ASHRAE 55-2010 was revised with a new adaptive comfort standard (ACS). This ACS was developed by the Center of the Built Environment by analysing over 21,000 sets of raw data (source). The ACS allows for warmer indoor temperatures for naturally ventilated buildings.

CEN Standard EN15251

Standard EN15251 was arranged by the department of Normalization of the European Committee (CEN), which includes several other aspects of the environments such as indoor air quality, lighting and acoustics. It is an independent database of thermal comfort responses in offices comes from the SCAT’s project, and is the basis of the adaptive relation included in European Standard EN 15251. The SCATs Project was a year-round study of the indoor environment in European offices, with particular emphasis on the thermal environment. The project consisted of a study of selected office-buildings in France, Greece, Portugal, Sweden and the UK. This standard uses the ASHRAE standard, but complemented with the consideration of mechanical cooling to assess building in free running mode.
3. Adaptive comfort

Table 8.5 The effect of adaptive behaviours on optimum comfort temperatures. Taken from BRE

<table>
<thead>
<tr>
<th>Action</th>
<th>Changes</th>
<th>Increase in comfort temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jumper/Jacket on or off</td>
<td>Changes Clo by ± 0.35</td>
<td>± 2.2K</td>
</tr>
<tr>
<td>Tight fit/Loose fit clothing</td>
<td>Changes Clo by ± 0.26</td>
<td>± 1.7K</td>
</tr>
<tr>
<td>Collar and tie on or off</td>
<td>Changes Clo by ± 0.13</td>
<td>± 0.8K</td>
</tr>
<tr>
<td>Office chair type</td>
<td>Changes Clo by ± 0.05</td>
<td>± 0.3K</td>
</tr>
<tr>
<td>Seated or walking around</td>
<td>Varies Met by ± 0.4</td>
<td>± 3.4K</td>
</tr>
<tr>
<td>Stress level</td>
<td>Varies Met by ± 0.3</td>
<td>± 2.6K</td>
</tr>
<tr>
<td>Vigour of activity</td>
<td>Varies Met by ± 0.1</td>
<td>± 0.9K</td>
</tr>
<tr>
<td>Different postures</td>
<td>Varies Met by ± 10%</td>
<td>± 0.9K</td>
</tr>
<tr>
<td>Consume cold drink</td>
<td>Varies Met by -0.12</td>
<td>- 0.9K</td>
</tr>
<tr>
<td>Consume hot drink/food</td>
<td>Varies Met by +0.12</td>
<td>+ 0.9K</td>
</tr>
<tr>
<td>Operate desk fan</td>
<td>Varies Vel by +2.0m/s</td>
<td>+ 2.8K</td>
</tr>
<tr>
<td>Operate ceiling fan</td>
<td>Varies Vel by +1.0m/s</td>
<td>+ 2.2K</td>
</tr>
<tr>
<td>Open window</td>
<td>Varies Vel by +0.5m/s</td>
<td>+ 1.1K</td>
</tr>
</tbody>
</table>

4. Local discomfort

Asymmetric Thermal Radiation

The radiant temperature asymmetry is the difference in temperature between two surfaces on opposite sides of the person. Asymmetric or non-uniform thermal radiation in a space may be caused by cold windows, uninsulated walls, cold products, cold or warm machinery, or improperly sized heating panels on the wall or ceiling. In residential buildings, offices, restaurants, etc., the most common causes are cold windows or improperly sized or installed ceiling heating panels (ASHRAE, 2013).

Warm or cold floors

The relation between floor temperature and thermal discomfort in offices is negligible. For people wearing normal indoor footwear, flooring material is insignificant (ASHRAE, 2013). Although the floor is of influence on the mean radiant temperature the effect can only be measured when people are bare foot or in case of schools playing on the ground. To save energy, insulating flooring materials (cork, wood, and carpets), radiant heated floors, or floor heating systems can be used to eliminate the desire for higher ambient temperatures caused by cold feet (ASHRAE, 2013).

Colour

It seems to be a commonly accepted idea that colour in a room influences the feeling of warmth. For instance an individual is presumed to feel warmer in an environment finished in a colour scheme in which red predominates (Fanger, 1972, p. 100).
Temperature variations with time.

Fluctuations in air temperature may affect the thermal comfort of occupants. Fluctuations under the direct control of individual occupants do not have a negative impact on thermal comfort. Fluctuations that occur due to factors that are out of the direct control of the individual occupant may have a negative effect on comfort. Fluctuations that occupants experience as a result of different environmental conditions are allowed as long as the conditions are within the comfort zone of the occupants.

Micro climate

Human response to draft has been studied mainly under isothermal conditions, airflow at temperature equal to room air temperature, both in whole body exposure to air movement (Fanger et al. 1988) and in exposure to locally controlled airflow (Fountain et al. 1994). This effect of controlling sub-areas in a space can be energy efficient. Thermal comfort is subjective and therefore it can be useful if each individual control its personal space. By giving the occupants control over their own environment they will accept higher temperatures.

A window is one of the locally provided air movement. Although this only will help for the people in the perimeter the possibility to open a window will increase the neutral temperature up to one degree (adaptive thermal comfort in Appendix) (ASHRAE, 2013).

View

Depending the location and the view, people can have a higher tolerance. In the presence of green people will accept higher temperatures before feeling too warm. The same occurs when people can see the horizon from their working position.

5. Secondary factors affecting thermal comfort sensation

Temperature, air speed, humidity, their variations, and personal parameters of metabolism and clothing insulation are primary factors that directly influence energy flow and thermal comfort. Many secondary factors, some of which discussed in this section, may or can have more subtle influence on the experience of thermal comfort.

Age

Studies reveal that thermal environments preferred by older people do not differ from those preferred by younger people. The lower metabolism in older people is compensated by a lower evaporative heat loss. The fact that young and old people prefer the same thermal environment does not necessarily mean that they are equally sensitive to cold or heat. In practice the ambient temperature level in the homes of older people
is often higher than that for younger people. This may be explained by the lower activity level of elderly people, who are normally sedentary for a greater part of the day (ASHRAE, 2013).

Adaptions

Research conducted by Fanger in the climate chambers that there is only a slight difference in preferred ambient temperature and physiological parameters in the comfort conditions. Indicating that people cannot adapt to preferring warmer or colder environments, and therefore the same comfort conditions can likely be applied throughout the world.

However, in uncomfortable warm or cold environments, adaptation often has an influence. People used to working and living in warm climates tolerate higher temperatures because they are used to it.

6. Psychometric chart

![Psychometric chart]

Figure 8.1

The psychometric chart, if applied with met 0.6 for summer and winter.
Appendix C. Natural Ventilation

1. Design considerations

Heat production computer

<table>
<thead>
<tr>
<th>iMac (Retina 5K, 27-inch, Late 2015)</th>
<th>27-inch Retina 5K display, 4.0 GHz Intel quad-core Core i7, 32GB 1866 MHz DDR3L SDRAM, 3TB Fusion Drive, AMD Radeon R9 M390 with 2GB GDDR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption</td>
<td>Thermal Output</td>
</tr>
<tr>
<td>Idle</td>
<td>CPU Max</td>
</tr>
<tr>
<td>63 W</td>
<td>240 W</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>iMac (Retina 4K, 21.5-inch, Late 2015)</td>
<td>21.5-inch Retina 4K display, 3.3 GHz Intel quad-core Core i7, 16GB 1866 MHz LPDDR3 SDRAM, 2TB Fusion Drive</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Thermal Output</td>
</tr>
<tr>
<td>Idle</td>
<td>CPU Max</td>
</tr>
<tr>
<td>40 W</td>
<td>119 W</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>*1 BTU/hr = 0.29307107 W (<a href="http://www.rapidtables.com/">http://www.rapidtables.com/</a>)</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.5 mixed mode ventilation strategies

<table>
<thead>
<tr>
<th>Contingency</th>
<th>NV + mechanical</th>
<th>NV + cooling</th>
<th>Adaptive comfort</th>
<th>Separate office</th>
<th>Open floor plan</th>
<th>Operable window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoned</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Complementary Zoned</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
2. Design calculations

Navier-Stokes equations

To describe the movement of a fluid substance the Navier-Stokes equations can be applied (Ortega, 2011).

Continuity

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \bar{u}) = 0 \]  

Momentum

\[ \rho \frac{\partial \bar{u}}{\partial t} + \rho \bar{u} \nabla (\bar{u}) = -\nabla p + \frac{\mu}{\rho} \nabla^2 \bar{u} + \rho f_m \]  

Energy

\[ \rho \frac{\partial C_p T}{\partial t} + \rho \bar{u} \nabla (C_p T) = -p \nabla \bar{u} + \bar{t} : \nabla \bar{u} + \nabla (k \nabla T) \]

These equations do not have an analytic solution; therefore usually a simplification is used to achieve an approximations. The number of Reynolds and the Rayleigh number are used for these simplifications, as dimensionless number.

Reynolds number

For Newtonian fluids the transition from laminar to turbulent flow takes place at a critical value of the quantity \( \rho u d_i / \mu \). This quantity is known as the Reynolds number \( Re \). The Reynolds number gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types for given flow conditions (Holland & Bragg, 1995).

\[ Re = \frac{\rho u d_i}{\mu} \]
Where \( u \) is the volumetric average velocity of the fluid, \( d_i \) is the internal diameter of the pipe, and \( \rho \) and \( \mu \) are the fluid’s density and viscosity. Under normal circumstances, the laminar-turbulent transition occurs at a Reynolds number of about 2100 for fluids flowing in pipes. Ortega states that when this number is high (Re > 1) the viscous forces can be neglected. In his work he cites that a laminar flow in ducts occurs when Re < 2300 and for Re > 4000 the flow is turbulent (Ortega, 2011). Resulting in transition phase where the flow is not fully laminar nor turbulent 2300 > RE < 4000 (transitional flow).

**Rayleigh number**

The Rayleigh measures the importance of buoyancy driven flow. When the Rayleigh number is low, heat transfer is primarily in the form of conduction; when it exceeds the critical value, heat transfer is primarily in the form of convection.

\[
Ra = \frac{g\beta \Delta T C_p \rho^2 L^3}{\mu k}
\]

In a pure natural convection the Rayleigh number measures the strength of the buoyancy induced flow. When Ra < 10^8 indicates an induced laminar flow and a transition to turbulent flow among 10^8 < Ra < 10^{10}.
Primary pressure losses

\[
[f \left( \frac{Re}{\varepsilon} \right)] (Ortega, 2011)
\]

\[
4f \left( \frac{Z}{D_h} \right) (Hazim B Awbi, 1994)
\]

The friction coefficient \( f \) can be estimated with the Moody chart (in appendix). \( L \) is the length of the duct, \( D_h \) is the hydraulic diameter of the duct and \( \varepsilon \) the rugosity. \( D_h \) is calculated with the following formula:

\[
D_h = \frac{2wd}{w+d}
\]

Where \( w \) is the duct width and \( d \) is the depth. For a narrow duct \((w > 10d)\):

\[
D_h \approx 2d
\]

Secondary pressure losses

\[
K_i \left( \frac{A}{A_i} \right) + K_o \left( \frac{A}{A_o} \right) + K_n \left( \frac{A}{A_n} \right)
\]

With \( K \) as the pressure loss coefficients; \( A \) is the cross-sectional area of the ventilation channel; \( A_i \) and \( A_o \) are the areas of the inlet and outlet respectively, but can be expand by multiple \( A_n \) components. These secondary components of the system have their own...
pressure loss coefficient $K_n$, and in the most of the cases can be calculated with charts. Secondary pressure losses can be due to inlet, outlet, nozzles and valves. Each component have a constant coefficient of pressure loss (Ortega, 2011).

$$\sum K_{\text{drop}} = 4f \frac{L}{D} + K_i \left( \frac{A}{A_i} \right) + K_p \left( \frac{A}{A_p} \right) + K_n \left( \frac{A}{A_n} \right)$$

Pressure loss circular pipe, vs square,

**Boundary layer**

For flows with high Re, the effect of the viscosity is neglected, but areas close to walls, the viscosity has to take into account because this area in the most of the cases affect to the solution. This area is the boundary layer and its study is very important to understand the behaviour of the solar chimney.

**Airflow**

Consider flow through the pipe-work shown in Figure 1.3, in which the fluid occupies the whole cross section of the pipe. A mass balance can be written for the fixed section between planes 1 and 2, which are normal to the axis of the pipe. The mass flow rate across plane 1 into the section $\rho_1 Q_1$ is equal to and the mass flow rate across plane 2 out of the section is equal to $\rho_2 Q_2$, where $\rho$ is the density of the fluid and $Q$ the volumetric flow rate. The mass balance can be written as (Holland & Bragg, 1995):

$$\text{Mass flow rate in} = \text{mass flow rate out} + \text{rate of accumulation within the pipe section}$$

$$\rho_1 Q_1 = \rho_2 Q_2 + \frac{\partial}{\partial t}(\rho \mu v)$$

*Figure 8.4 Flow through a pipe of changing diameter. (Holland & Bragg, 1995)*
The wind and stack pressures will be equal to the sum of the velocity pressure at the inlet and outlet and the pressure losses in the flow path. For a channel the pressure losses are given by (Hazim B Awbi, 1994):

\[
\sum K_{\text{drop}} = \left[ 4f \frac{L}{D_h} + K_i \left( \frac{A_i}{A_i} \right) + K_p \left( \frac{A_o}{A_o} \right) + K_n \left( \frac{A_n}{A_n} \right) \right] \cdot \frac{1}{2} \rho v_m^2
\]

where the \(K\)'s are the pressure loss coefficients; \(A\) is the cross-sectional area of the ventilation channel; \(A_i, A_o, A\) are the areas of inlet, damper and exit respectively; \(z\) is the height between two openings; \(p\) is the density; \(V_m\) is the mean air speed in the channel; \(D_h\) is the hydraulic diameter of the channel and \(f\) is the friction factor for the channel wall. The hydraulic diameter is given by:

\[
D_h = \frac{2wd}{w+d}
\]

Where \(w\) is the duct width and \(d\) is the depth. For a narrow duct \((w > 10d)\):

\[
D_h \approx 2d
\]

**Boussinesq model**

The problem of in this equation that both the energy and the momentum Navier-Stokes equation are combined, leaving two unknown values \(\Delta \rho\) and \(\Delta P_{\text{stack}}\). The solution can be found by iteration, must faster is to use the Boussinesq model. This model treats the density as a constant value in all the equations except in the buoyancy term of the momentum equation (Ortega, 2011).

\[
\rho = \rho_0 (1 - \beta \Delta T) \rightarrow \beta \Delta T \ll 1
\]

\[
\Delta P_{\text{stack}} = \rho gh \beta \Delta T
\]

Where \(\beta\) is the thermal expansion coefficient.
Reference wind

The reference wind speed $v_r$ is usually determined for a point corresponding to a characteristic height such as the total height of the building or the height of an opening above the ground. The equation determining the wind speed at a certain level is:

$$[\text{EQ 18.}] \quad \frac{v_r}{v_{10}} = cz^a$$

Where $v_{10}$ is the meteorological wind speed for a height of ten meters above the ground (in case the wind $C$ and

$$[\text{EQ 19.}] \quad \frac{v_i}{v_r} = F(1 - 0.82a)$$

Friction in the chimney, for ventilation ducts.
FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE
Appendix D. Design

1. Cross & stack ventilation design tool

In order to get a yearly overview of effectiveness of a certain window dimensions an excel spreadsheet with climate date of the year 2002 is composed with weather data from Climate consultant. Imported data are relative humidity, temperature, wind direction and speed, radiation on vertical surface for 0, 45, 90, 135, 180, 225, 270, 315 degrees from the north plane. Additional data for light intensity are collected but not used in this model.

Functionality

With the use of this tool the dimensions of a simple solar chimney in combination with cross ventilation can be tested. Based on opposite similar façades, the tool gives the volume flow as a percentage of the necessary airflow to achieve comfortable temperature with 10% Percentage People Dissatisfied (PPD) according to Ashrae’s adaptive comfort standard (2013). For four main orientations. To incorporate relative humidity the upper limit for cross-ventilation is limited to a maximum of 80% RH. Above the 80% the supply of air is via centralized supply. The model has some limitations that will be discussed in the following paragraphs.

Overview

The results are shown on the first tab beneath the parameters. The results are accumulations of values one and zero. Due to the wind gradient results can be different due to the height therefore 4 different levels have been monitored (10, 50, 150 and 250 meter height).

The results for the solar chimney are for all the RH levels and therefore don’t follow the list filter (figure 6.2) and uses the simple sum command. The results for cross ventilation

Figure 8.1 Hybrid strategy for the model based on available natural resources

Figure 8.2 Relative humidity level can be changed via list filter in Resume tab column E.
only counts for the allowed RH levels (sum of subtotal). A full year counts 3650 hours, this is 7 days a week from 9:00 till 18:00. Of these hours the stack effect and cross ventilation are counted separately.

- Wind has 2557 hours where RH≤80%
- Solar has 3650 hours

The results are shown in two categories. The 80%RH 100% ventilation capacity shows the amount of hours the solar chimney is able to extract the necessary volume (defined by the demand) and cross ventilation is sufficient to deal with the heat. The SUM 80%RH Hybrid mode is showing the amounts of hours it is able to save of electricity. It is calculating as well the amount of hours the chimney is not able to solely rely on stack effect, it counts the percentage of air the chimney can remove and puts this percentage in hours. Two hours of 50% capacity is (2 * 0.5) accounted for 1 hour. The steps are for each 10% (roundup to below). Because cross ventilation is affiliated with the RH level it cannot deliver appropriate air quality and is not accounted for in the SUM 80%RH HYBRID MODE. It is showing the same values as in the left category.

- 100% mode: wind 100% + solar stack effect 100%
- Hybrid mode: wind 100% + solar stack effect 10 – 100%.

To prevent double counts the hours when cross ventilation is possible (value 1) are compared with the values of stack effect (values 1). If both are 1, they can provide thermal comfort in that hour and thus needs to be only counted once if we want to know the effectiveness of NV in general. In the overlap all the double counts are counted and correctly implemented in the total.

Parameters

Above the results the parameters are shown. Some of them can be changed (orange), some of them are formed due to other parameters (grey) and some are not changing (white).
Office zone

**Dimensions**

Firstly the volume of the office zone. This is defined by a zone due to the lack of ability to account for multiple chimneys per zone. The zone is defined as a measure for the height of the chimney. The width of the zone is the height of the chimney in floor levels. In this case a chimney of 4 levels has a zone width of 8 times a unitized curtain wall module, of which 4 units are open for cross ventilation and 4 are chimneys. Depth is kept at 15 meters, as a maximum for optimal cross ventilation, but can be changed for other cases. The height is from the floor to the ceiling. The volume is calculated out of these parameters (Length x Width x Height).

![Office zone parameters]

*Figure 8.5 Parameters for office zone and images to clarify*

**Heat load**

The amounts of occupants per zone defines the amount of internal heat load. Each occupant counts a radiation of 200 Watts. In case the length of the chimney is tested, the zone width will change, and therefore the amount of occupants has to be adapted as well. In case of different destinations, the occupant radiation can be adapted. With 200W a minimum for an office worker is accounted.

**Reference wind**

The reference wind is build up out of two exponents, the Vreff coefficient in figure 6.2 (0.33 for urban area) and the c value in figure 6.3 (0.17 for open land). Together with the altitude of the building (reference height in figure 6.3) it forms the wind gradient defining \( v_r \):

\[
[\text{EQ. 20.}] \quad v_r = V_{\text{ref}} \cdot \left(\frac{400}{10}\right)^0.17 \cdot \left(\frac{300}{400}\right)^0.33
\]
Wind

Effective opening \( Ae \)

The office is generalized by a tube with a discharge coefficient \( C_D \). For the office 0.9 is used this is partly due to the relative low resistance in an open office plan. Openings are parallel and should be unified in the effective opening area by the parallel formula;

\[
\text{[EQ 21.]} \quad \frac{1}{Ae_{(parallel)}^2} = \frac{1}{(A_1 \cdot C_D)^2} + \frac{1}{(A_2 \cdot C_D)^2}
\]

Whereas \( A_1 \) is defined by the openings in the façade on each side. Because the facades are mirrored the same opening areas are used (\( A_1 = A_2 = A_{eff} \)).

\[
\text{[EQ 22.]} \quad A_e = \sqrt{\frac{1}{A_{eff}^2 \cdot C_D^2} + \frac{1}{A_{eff}^2 \cdot C_D^2}}
\]

\( A_{eff} \) is the effective opening area on one side, consisted of several windows in series.

\[
\text{[EQ 23.]} \quad A_{e(series)} = (A_1 \cdot C_D) + (A_2 \cdot C_D)
\]

The amount of windows depends on the size of the zone, defined by the height of the chimney by value \( N \). Each panel consist of three possible openings.

\[
\text{[EQ 24.]} \quad A_{eff} = N(h_1 \cdot w_1 \cdot C_{D1}) + N(h_2 \cdot w_2 \cdot C_{D2}) + N(h_3 \cdot w_3 \cdot C_{D3})
\]

---

Figure 8.6 Parameters for cross ventilation
Chimney

The third parameter box is the CHIMNEY. This contains the parameters to define a rectangular chimney with surface $A_e$. Not to confuse with the $A_e$ of the window for cross ventilation. The $A_e$ of the chimney is based on two parallel openings and these should be the smallest in diameter. Extra resistance modules can be added with the parallel formula, but these are not implemented in this model. But should be implemented in case the chimney is thoroughly calculated as in the appendix including the thermal and velocity boundaries.

\[
A_e = \sqrt{\frac{1}{A_1 C_D^2}} + \frac{1}{A_1 C_D^2}
\]

\[
A_1 = \text{width of chimney} \cdot \text{depth of chimney}
\]

Other parameters in this box are the glass transmittance. This is depending on the glass. Normally part of the sunlight is reflected, absorbed and transmitted.

The heat capacity of air is used to calculate the capacity of watt that can be absorbed, this is a value that is influence by the humidity in real life. In this case it’s a fixed value (and a copy of the value in parameter box WIND). The weight of the air is used to calculate the mass flow in the chimney later on (also a copy of the value in parameter box).

\[
\rho = 353 / K
\]

$f$ is a number that signifies the way radiation is released onto the chimney. 2 is for an equally spread, if all the heat is focused on the bottom, the value would be 1.

**Demand**

Ventilation needed is calculated in the tab of demand according the following formula.
With this formula there is no influence of windflow in the office increasing the comfort temperature. It can be that the airflow in the office will allow a higher comfort temperature. Results of Designbuilder don’t show high airflows <0.2m/s in the office and can therefore be neglected. Comfort temperature is calculated via the formulas of de Dear. With 10% people dissatisfied it gives the following equation.

\[ T_{\text{comfort 10\%PPD}} = T_{\text{air}} \cdot 0.31 + 20.3 \]

Wind

Wind pressure

The demand volume is compared with the crossventilation flow in the tab wind. The basic formula to calculate the wind pressure is used.

\[ P_w = \frac{1}{2} \rho v_r^2 \cdot C_p \]

Where the pressure coefficient \( C_p \) is depending on the wind angle. The \( C_p \) varies with height and the different values are given in the tab \( C_p \). For each façade the different coefficients are given and for opposing facades cumulated to use for cross ventilation with parallel windows. With the IF command the angle of the wind is fitted with the right value.
The reference wind is known (see reference wind) and the rho as well.

Cross ventilation flow

All the parameters for the cross ventilation are known at this moment and now the calculation for the airflow can be done.

\[ Q = C_d A_e \sqrt{\frac{2\Delta P}{\rho}} \]  

Pressure solar chimney

Stack pressure

The pressure in the solar chimney is calculated via the gravitational force, temperature difference, and the height.

\[ \Delta P_{stack} = \rho gh \frac{\Delta T}{T_{air}} \]  

Where the temperature via the following
\[ \Delta T = \frac{\Delta \text{Heat}^2 \cdot T_{air}^\frac{1}{3}}{(2gh)^\frac{1}{3} \cdot (\rho f c_{air} c_A e)^\frac{1}{3}} \]

\[ \Delta \text{Heat} = \text{height} \cdot \text{width} \cdot \text{radiation} \cdot \text{transmission glass} \]

\[ T_{air} = \text{climate data} \]

Flow chimney

The stack pressure is not the only pressure accounted for on the airflow of a solar chimney. The pressure coefficient on the side of the outlet can add a positive or negative influence. In case there is a negative pressure on the exhaust the airflow will be extra induced and vice versa. The same formula of airflow is used only with addition of wind pressure.

\[ Q = C_d A_e \sqrt{\frac{2(\Delta P_{\text{stack}} + P_{\text{wind stack exhaust}})}{\rho}} \]

Correction flow chimney

Implementation of the flow derived from the internal heat load. Adaption off f factor and heat generated by occupants. This is added to the chimney in the same ratio as the heat is extracted.

\[ \Delta \text{Heat} = (\text{height} \cdot \text{width} \cdot \text{radiation} \cdot \text{transmission glass}) + (W_{\text{occupant}} \cdot n_{\text{occupants}} \cdot \text{Ratio}_{\text{chimney}}) \]

\[ \text{Ratio}_{\text{chimney}} = \frac{\text{Volume}_{\text{chimney N}}}{\text{Volume}_{\text{chimney N1}} + \text{Volume}_{\text{chimney N2}}} \]

Whereas the chimney N1 and N2 are the opposite chimneys.
Increased comfort temperature by airflow.

Results

The results tab gives the information about the flows. The cross ventilation is based on two facades, and the solar on one façade. With the mirrored façade, the chimney is on both sides of the office and the two chimney volumes are summed up to form $Q_{\text{solar}}$.

The hybrid mode will act in case the wind pressure is stronger than the stack pressure and will put the negative flow to a stop (all the zero values).
## 2. Design results

### Pressure coefficients

<table>
<thead>
<tr>
<th>10 meter</th>
<th>Pressure coefficient on surface</th>
<th>Pressure differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NW</td>
<td>W</td>
</tr>
<tr>
<td>0</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>0.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>30</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>40</td>
<td>0.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>50</td>
<td>0.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>60</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>70</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>80</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>90</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

### Pressure differences

<table>
<thead>
<tr>
<th>10 meter</th>
<th>Pressure coefficient on surface</th>
<th>Pressure differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NW</td>
<td>W</td>
</tr>
<tr>
<td>0</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>0.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>30</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>40</td>
<td>0.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>50</td>
<td>0.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>60</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>70</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>80</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>90</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

### Diagram

- The diagram illustrates the pressure differences across different wind directions (N, NW, W, SW, S, SE, E, NE, N-S, E-W, NE-SW, NW-SE).
- The pressure coefficients on the surface are indicated for each direction.
- The pressure differences are shown as differences from a reference point.
<table>
<thead>
<tr>
<th>Pressure coefficient on surface</th>
<th>Pressure differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NW</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure coefficient on surface</th>
<th>Pressure differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NW</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
</tbody>
</table>

250 Meter

<table>
<thead>
<tr>
<th>Pressure coefficient on surface</th>
<th>Pressure differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NW</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>Main function</td>
<td>Primary functions</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Create a durable construction</td>
<td></td>
</tr>
<tr>
<td>Enable water and impair management in construction</td>
<td></td>
</tr>
<tr>
<td>Keep materials and components in working condition</td>
<td></td>
</tr>
<tr>
<td>Refine the design and management processes</td>
<td></td>
</tr>
<tr>
<td>Learn reasonable production methods</td>
<td></td>
</tr>
<tr>
<td>Allow reasonable assembly methods</td>
<td></td>
</tr>
<tr>
<td>Create a comfortable temperature</td>
<td></td>
</tr>
<tr>
<td>Create a comfortable humidity level</td>
<td></td>
</tr>
<tr>
<td>Maintain within a given range</td>
<td></td>
</tr>
<tr>
<td>Block unwanted noise</td>
<td></td>
</tr>
<tr>
<td>Create visual comfort</td>
<td></td>
</tr>
<tr>
<td>Minimize energy consumption during use</td>
<td></td>
</tr>
<tr>
<td>Minimize embodied energy</td>
<td></td>
</tr>
<tr>
<td>Minimize energy for production, transport, assembly</td>
<td></td>
</tr>
<tr>
<td>Enable reuse and recycling</td>
<td></td>
</tr>
<tr>
<td>Generate energy</td>
<td></td>
</tr>
<tr>
<td>Screen energy</td>
<td></td>
</tr>
<tr>
<td>Protect the facade</td>
<td></td>
</tr>
<tr>
<td>Support use of the building</td>
<td></td>
</tr>
<tr>
<td>Enable functionality</td>
<td></td>
</tr>
<tr>
<td>Maintain facade building value</td>
<td></td>
</tr>
<tr>
<td>Enable architectural possibilities</td>
<td></td>
</tr>
<tr>
<td>Respond to urban context</td>
<td></td>
</tr>
<tr>
<td>Enable functional intention of building</td>
<td></td>
</tr>
<tr>
<td>Create appropriate interior perception</td>
<td></td>
</tr>
<tr>
<td>Effective preloading</td>
<td></td>
</tr>
<tr>
<td>Induce arrangement</td>
<td></td>
</tr>
<tr>
<td>Induce proportion</td>
<td></td>
</tr>
<tr>
<td>Induce scale</td>
<td></td>
</tr>
<tr>
<td>Apply texture</td>
<td></td>
</tr>
<tr>
<td>Apply colour</td>
<td></td>
</tr>
<tr>
<td>Apply material</td>
<td></td>
</tr>
<tr>
<td>Induce rhythm</td>
<td></td>
</tr>
</tbody>
</table>
Table 8.6 Effectiveness of combination wind façade and solar chimney. Iteration of width components and ceiling height. Thickness of chimney walls is not incorporated For chimney length 20m Without local pressure losses

<table>
<thead>
<tr>
<th>Chimney width (m)</th>
<th>N-S</th>
<th>W-E</th>
<th>NW-SE</th>
<th>NE-SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 0.6              |     |     |       |       |
| 0.7              |     |     |       |       |
| 0.8              |     |     |       |       |
| 0.9              |     |     |       |       |
| 1.0              |     |     |       |       |

FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE | 229
0.5 meter entree height (results are from simulation and contains errors)

<table>
<thead>
<tr>
<th>Altitude</th>
<th>10</th>
<th>50</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth 0.5m [entree 0.5] hrs.</td>
<td>214</td>
<td>215</td>
<td>216</td>
<td>217</td>
</tr>
<tr>
<td>Depth 0.5m [entree 0.9] hrs.</td>
<td>223</td>
<td>224</td>
<td>223</td>
<td>224</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude</th>
<th>10</th>
<th>50</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth 0.5m [entree 0.5] hrs.</td>
<td>254</td>
<td>258</td>
<td>248</td>
<td>250</td>
</tr>
<tr>
<td>Depth 0.5m [entree 0.9] hrs.</td>
<td>268</td>
<td>271</td>
<td>257</td>
<td>259</td>
</tr>
</tbody>
</table>
Table 8.7 Hours without HVAC and effective surface $A_e$, for two and one story high chimneys.

<table>
<thead>
<tr>
<th>Chimneys</th>
<th>Wind scale</th>
<th>2 story chimney 7.5m height</th>
<th>1 story chimney 3.5m height</th>
<th>1 story chimney height</th>
<th>2 story chimney height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>width m</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.27</td>
<td>0.54</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.54</td>
<td>0.81</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.81</td>
<td>1.35</td>
<td>2.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.35</td>
<td>2.16</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.16</td>
<td>2.43</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.43</td>
<td>3.12</td>
<td>4.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.12</td>
<td>4.41</td>
<td>5.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.41</td>
<td>5.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.89</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE | 231
The variation in number of chimneys for single story chimney heights. One to ten chimneys with variable width and effective section area in the right two columns.

<table>
<thead>
<tr>
<th>chim</th>
<th>mV</th>
<th>width</th>
<th>N S</th>
<th>W E</th>
<th>HVAC-S</th>
<th>NEC-Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>1</td>
<td>0.66</td>
<td>0.59</td>
<td>0.54</td>
<td>0.52</td>
<td>0.52</td>
<td>0.51</td>
</tr>
<tr>
<td>2</td>
<td>0.73</td>
<td>0.67</td>
<td>0.64</td>
<td>0.62</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
<td>0.75</td>
<td>0.72</td>
<td>0.70</td>
<td>0.69</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>0.87</td>
<td>0.83</td>
<td>0.80</td>
<td>0.78</td>
<td>0.77</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>0.95</td>
<td>0.91</td>
<td>0.88</td>
<td>0.86</td>
<td>0.85</td>
<td>0.84</td>
</tr>
<tr>
<td>6</td>
<td>1.03</td>
<td>0.99</td>
<td>0.96</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>7</td>
<td>1.12</td>
<td>1.08</td>
<td>1.05</td>
<td>1.03</td>
<td>1.02</td>
<td>1.01</td>
</tr>
<tr>
<td>8</td>
<td>1.20</td>
<td>1.16</td>
<td>1.13</td>
<td>1.11</td>
<td>1.10</td>
<td>1.09</td>
</tr>
<tr>
<td>9</td>
<td>1.29</td>
<td>1.25</td>
<td>1.22</td>
<td>1.20</td>
<td>1.19</td>
<td>1.18</td>
</tr>
<tr>
<td>10</td>
<td>1.37</td>
<td>1.34</td>
<td>1.31</td>
<td>1.29</td>
<td>1.28</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**Table 8.8 Without HVAC for different zoning for 1 story chimney**
Optimization of chimney height step 0.5 for single story chimney.

### Table 8.9 Overview hours without HVAC for chimney with variable height, 4 chimneys with width variable and depth 0.9m.

<table>
<thead>
<tr>
<th>Wind Component m</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
<th>0.55</th>
<th>0.60</th>
<th>0.65</th>
<th>0.70</th>
<th>0.75</th>
<th>0.80</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>NE</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>SE</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>SW</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
</tbody>
</table>

Optimization for variable height.

### Table 9.6 Variable height for chimney.

<table>
<thead>
<tr>
<th>chimney height</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
<th>0.55</th>
<th>0.60</th>
<th>0.65</th>
<th>0.70</th>
<th>0.75</th>
<th>0.80</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>NE</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>SE</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
<tr>
<td>SW</td>
<td>515</td>
<td>510</td>
<td>505</td>
<td>500</td>
<td>495</td>
<td>490</td>
<td>485</td>
<td>480</td>
<td>475</td>
<td>470</td>
</tr>
</tbody>
</table>
**Optimization of chimney height, step 0.1 for single story chimney.**

**Table 8.10 Overview hours without HVAC for chimney with variable height. 4 chimneys with width variable and depth 0.9m.**

<table>
<thead>
<tr>
<th>Chimney Height (m)</th>
<th>Width (m)</th>
<th>Chimney Height (m)</th>
<th>Width (m)</th>
<th>Chimney Height (m)</th>
<th>Width (m)</th>
<th>Chimney Height (m)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.40</td>
<td>0.45</td>
<td>0.50</td>
<td>0.55</td>
<td>0.60</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>0.85</td>
<td>0.50</td>
<td>0.55</td>
<td>0.60</td>
<td>0.65</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>0.80</td>
<td>0.75</td>
<td>0.80</td>
<td>0.85</td>
<td>0.90</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>0.85</td>
<td>0.90</td>
<td>0.95</td>
<td>1.00</td>
<td>1.05</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>0.90</td>
<td>1.00</td>
<td>1.05</td>
<td>1.10</td>
<td>1.15</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>0.95</td>
<td>1.10</td>
<td>1.15</td>
<td>1.20</td>
<td>1.25</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>1.00</td>
<td>1.20</td>
<td>1.25</td>
<td>1.30</td>
<td>1.35</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>1.05</td>
<td>1.30</td>
<td>1.35</td>
<td>1.40</td>
<td>1.45</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>

**Highest values**

- Wind direction
  - N: 0.43
  - W: 0.43
  - SW: 0.43
  - NW: 0.43
  - SE: 0.43
  - NE: 0.43

- Chimney height
  - 0.85 m: 0.43
  - 0.90 m: 0.43
  - 0.95 m: 0.43
  - 1.00 m: 0.43
  - 1.05 m: 0.43
  - 1.10 m: 0.43
  - 1.15 m: 0.43
  - 1.20 m: 0.43
  - 1.25 m: 0.43
  - 1.30 m: 0.43
  - 1.35 m: 0.43
  - 1.40 m: 0.43
  - 1.45 m: 0.43
  - 1.50 m: 0.43

- Wind speed
  - 0.85 m: 0.43
  - 0.90 m: 0.43
  - 0.95 m: 0.43
  - 1.00 m: 0.43
  - 1.05 m: 0.43
  - 1.10 m: 0.43
  - 1.15 m: 0.43
  - 1.20 m: 0.43
  - 1.25 m: 0.43
  - 1.30 m: 0.43
  - 1.35 m: 0.43
  - 1.40 m: 0.43
  - 1.45 m: 0.43
  - 1.50 m: 0.43
### Composition of chimney

#### Solar chimney glazing ratio.

To challenge the effect of glass versus opaque as positive effect on the stack effect. Three settings have been tested. A chimney with 25% glass (75% absorbing body), 50% glass (50% absorbing body) and 75% glass (25% absorbing body).

### Setting

Without the influence of wind, next to the chimneys there is a mass, simulating a chimney next to the tested one. The shading effect of other chimneys on the tested one is with these dummy chimneys included in the test as well.

### Materialization

Four materials are tested, single glazing, double glazing, a simple partition wall and a high insulated wall. Where the absorbing black body is of steel deck plate.

### Results

<table>
<thead>
<tr>
<th>Rating</th>
<th>System</th>
<th>North</th>
<th>50% glass</th>
<th>75% glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>Double glazing + simple partition</td>
<td>6</td>
<td>6+</td>
<td>6+</td>
</tr>
<tr>
<td></td>
<td>Same U value 2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>5+</td>
<td>5+</td>
</tr>
<tr>
<td>--</td>
<td>Single glazing + simple partition</td>
<td>5+</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.9 &amp; 2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East</td>
<td>5</td>
<td>4+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>4</td>
<td>4+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>5+</td>
<td>5+</td>
</tr>
<tr>
<td>+++</td>
<td>Single glazing + high insolated wall</td>
<td>North</td>
<td>8+</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>5.9 &amp; 0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East</td>
<td>7+</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>++++</td>
<td>Double glazing + high insolated wall</td>
<td>North</td>
<td>9-</td>
<td>9-</td>
</tr>
<tr>
<td></td>
<td>2.5 &amp; 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>7+</td>
<td>7</td>
</tr>
</tbody>
</table>
The best performance results of the chimney are scored with a system of double glazing in combination with a good insulated wall. The second best scores are for the system based on 50% glass with the same composition of materials. The relation between black body and performance is visible in the results in case the wall can isolate well.

3. Interview façade builder Scheldehou

Friday the 10th of May I have visited the factory of Scheldehou in Middelburg. This company is one of the lead façade builders. Scheldehou mainly produces facades for London, but the permasteelisa group of which they are a member does engineering, building and installing of facades worldwide. As façade builder they are in the middle between realisation and design requirements of the architects what makes them an interesting consultor for the façade design in thesis. I spoke with Boris Kock about the following topics:

- Composition of the façade
  - Connection chimney to façade
  - Aluminium
- Stiffness of the chimney
  - Structural glazing for the chimney
  - Depth of the aluminium profile
  - Aluminium sandwich panel
- Structural part
  - Width of the panelling
  - Support anchors
- Openings
  - Pivot windows
  - Grill
  - Motorized support windows
- Costs
- Transport
- Cold bridges

Composition of the façade

Connection chimney to façade

After showing my ideas about the façade, the first thing he mentioned was the connection between façade and the chimney, “we need to cut that loose”. Separating the two elements who be more logical because of two reasons: standardization and subcontractors. “We don’t make the façade we order different components and put them together”.

An aluminum frame can be customized by milling and welting, but not easily combining two separate mullions and unified them. It is easier to ask the supplier of the sandwich
panel to add a pin or a sleeve. In this way the two elements can be build separately what makes transport easier and stand profiles can be used. The actual connection can be mounted on the existing profiles. Attaching the two components close to the building site, depending on the space at the building site, can be easily done.

Aluminum

With the amount of openings the s

Stiffness of the chimney

- Structural glazing for the chimney
- Depth of the aluminium profile
- Aluminium sandwich panel

Structural part

- Width of the panelling
- Support anchors

Openings

- Pivot windows
- Grill
- Motorized support windows

Costs

Transport

Fotos
Table D8.11 Photos made in the factory of Scheldebouw in Middelburg

Pivot window
Pivot window

Pivot window
Pivot window decentral axe
Aluminum box attached to facade  Structural glass (the Shard, London)

Structural glass  Rain and dirt ‘flipper’
4. Architecture

Airtight rubber profile all sides  Aluminum connector to panel above
Different chimney forms. The rectangular box has the lowest loss.
Final Design
Appendix E. Reference projects

Naturally ventilated tall buildings are very unusual. It is difficult to deal with the high winds and the potential danger of opening windows in high levels. Tall buildings on the traditional American model usually have deep plans, in which many of the occupants are too far from the perimeter of the building to benefit from natural light and ventilation. Permanent artificial light and air conditioning are therefore the norm. In Germany, however, planning regulations specify that all office workers should have a view out of the building, which inevitably means a shallower plan.

Nevertheless, the risk of coping with natural ventilation in tall buildings is considerably higher than those of low-rise structures. The aspects to be considered include the potential greater magnitudes of wind and buoyancy effects at higher levels. Consequently, further cares should be taken with regard to envelop, opening design and surroundings for natural ventilation in tall buildings. The general objective of this chapter is to learn from the past and to propose a conceptual building configuration for naturally ventilated tall buildings in a hot and humid climate. The system effectiveness and ventilation strategies being employed in each case study are reviewed for the benefit of applying similar techniques to tall buildings in Singapore.

1. Brise Soleil

Brise Soleil, a forgotten passive sun protection method to protect against the sun. The term “Brise Soleil” refers to a rigid sun protection system, which most often consists of fixed slats or sun protection grids (urbanalyse, 2012). Attached to the outside facade in front of windows or across the whole building surface. Traditionally used in North Africa, Le Corbusier integrated it into modern architecture and constructed them as massive concrete, or from covered steel created, shelf-like protrusions, as, for example, on his buildings in Chandigarh, India.

Ministry of Education and Health Building, Brazil

The Ministry of Education and Health Building is considered as a turning point in Brazilian architecture. The project was developed by the architects Afonso
Eduardo Reidy, Carlos Leão, Ernani Vasconcelos, Jorge Moreira, and Oscar Niemeyer, coordinated by Lúcio Costa and counted with Le Corbusier as consultant.

The southwest façade was considered to be covered with sunlight during the early morning for a short period of the year, and therefore cladded with large glass windows to let in the lightest and also to secure a good view of the bay. The northwest façade shows a Brise Soleil to deal with local conditions. Horizontal adjustable blades of fiber-cement fixed to large concrete vertical blades (Naves et al.).

The project of the Brise Soleil divided the façade into boxes measuring 5m x 2m, with 1.3m depth, and 3 horizontal panels fixed to the sides, projecting themselves 50cm beyond the window. The louvres are developed for the mid-day sun in summer, and for a 45 degree winter sun, Strategies for dispelling the heat that formed between the sun-breaker and the interior of the building were found necessary, thus the 50 cm space between the Brise Soleil and the window.

![Figure 8.2 slats are high positioned to optimize the view. Slats are 50cm offset from the window.](image1)

![Figure 8.3 Northwest façade, with vertical fixed lamellas and horizontal moveable dark slats.](image2)

![Figure 8.4 Mechanism to rotate the horizontal slats.](image3)

Due to the relative movement of the sun, the use of horizontal louvers is useful. Near the equator, the protection offered by overhangs is more effective and the slats can be designed in a way that avoids a significant reduction of the visual field. The luminous fields generated by the louvers are more stable and penetrate deeper into the room, resulting in significant energy saving. For most of the time during the summer months, the blinds do not receive direct solar radiation. Therefore, they are not justified as a solar protection measure and their dark colour obstructs an optimal day-lighting balance.

If we consider white-painted blinds, the situation is significantly altered. Even under a cloudy sky, the light distribution with louvers is better than without them. It could be said that the reflection coefficient of a set of louvers is the more critical aspect for day-lighting. Slats with a reflectivity of 0.8 or higher (white) produce better luminous output than a window without blinds, and this may hold even under an overcast sky. Therefore, blades of adequate size and finished with a light colour in a northern orientation for the southern hemisphere are both a safe and necessary choice from the thermal and lighting point of view (Melendo, Lainez, & Verdejo, 2008).
Analysis - strengths

+ A system of vertical fins is successful for blocking all the direct sun light.
+ The horizontal fins are adaptive which allows more visuals during the day, and can be optimized for daylight entrance due to reflectivity of the slats.
+ The Concrete horizontal and vertical fins absorb the direct solar radiation.
+ The high position of the horizontal fins doesn’t interfere with the view.

Analysis – thoughts

– If the slats would have been white they work better for luminance values inside.
– Maybe the concrete slabs are quite heavy.

Torre Cube, Mexico

The tower consist of three funnel shaped timber-clad office wings cantilevered dramatically between and from three concrete cores. The three office wings vary in size. Typically being 105, 125 and 175 square meters in floor area. Apart from being the primary structural elements, the three cores also contain all the service facilities and vertical circulation elements within the building. The post tensioned cantilevered slabs allow for open-plan, column-free interiors within the office spaces themselves. The office spaces are a maximum of 12 meters in depth (measuring to the central void) and average approximately 12 meters in width. The central void is part of the natural ventilation system and brings light into the offices.

![Figure 8.5, 9.6, 9.7 Torre Cube view from inside and exterior cladding.](image)

The mild Guadalajara climate allows for natural ventilation throughout the entire year, without reliance on mechanical ventilation, heating or cooling. The external facades of the three office wings employ an open rain screen/ Brise Soleil façade and floor-to-ceiling sliding glass windows. The outer diaphanous screen consist of a wooden latticework made from thin, threated pine patterns on a steel frame acting as a Brise Soleil, protecting the offices from glare and solar heat gain and acting as protecting from falling out of the full-height sliding windows. In addition this outer screen acts as a partial buffer against wind-driven ventilation into the offices, reducing the speed of the airflow. The
wooden latticework panels can slide horizontally (manual operated by the office occupants), giving a degree of flexibility to the amount of shade and controlling the airflow into the offices. The intermediate zone between the two façade layers has grated floor panels at each floor, which permit access into the space, but do not prevent vertical airflow within the space.

Air is drawn into the office space through sliding windows form the façade and exhausted into the void through the sliding windows in the inner facing façade. Stack effect in the atrium provides additional uplift through negative pressure that pulls air out of the offices to be exhausted at the top of the building. The ventilation strategy of Torre Cube can thus be summarized as a combination of cross-ventilation assisted by significant stack in the central void.

Analysis - strengths

+ Rare example of truly natural ventilated office, not particular high-rise.
+ Positioning of the service core to the sides allowing for a free floorplan.
+ Each office has two facades, one on the outside one on the void side.
+ The Brise-soleil functions as wind breaker and as a sunscreen
+ Stack effect reduces the dependence on wind
+ Fan-shaped office space helps funnelling air into the central void and improves cross ventilation.
+ Concrete structure is not used as thermal mass, but can be an additional feature.

Analysis – thoughts

– Predominant wind can give advantage to particular office.
– The three story sky gardens have negative effect on the stack effect.
– Direct control can give advantage to some of the occupants.
– Durability of the wooden screens.
– Future developments can significantly affect the wind patterns around the building.
– Daylight level is low.
Figure 8.8 Façade section drawings of Torre Cube (Wood & Salib, 2013).
2. Monsoon window

The State Mortgage Building, Sri Lanka

Bawa was commissioned to design the 12-storey State Mortgage Bank building (now known as Mahaweli Building) in the heart of Colombo, Sri Lanka, by the government in 1972, but midway through the project there was a change of government that resulted in it being re-designated as the headquarters of the Mahaweli Ministry and a delay in completion of the construction to 1978.

![Image of building]

Figure 8.3 & 9.4 Form of the building is optimized for prevailing wind.

Building Shape and orientation

The site was an awkward and irregular shape, wedged between the Beira Lake and Hyde Park. In order to create a plan form which would respond aerodynamically to the prevailing winds while reducing solar gain, and which would give a maximum footprint, thus reducing the number of floors. The resultant profile also results in an elegant building that changes dramatically when seen from different angles. It appears slender from certain angles and much broader from others.

The building facades face predominantly north and south to minimize solar gain which is important in the tropical climate and the orientation of the building is such that Northeast and Southwest monsoon winds can be maximised for ventilation (prevailing wind direction of Colombo is south-west). It also has an aspect ratio in its built form and a ratio of volume to surface that are within the recommendation for an energy-efficient building in the tropics (Kiang & Robson, 2006).

Natural ventilation and day light

The design adopted a twin core layout. The cores serve as solar buffers, reducing heat gain into the building. The main core consists of lifts, staircase, toilets and entrance lobby that are all naturally ventilated. The lobby is very bright and airy and offers views of the
city. The secondary core houses the escape staircase which is also naturally lit and ventilated with operable windows.

To achieve continuous natural ventilation, the cross section allows air movement at different body levels. Above the windows are precast ventilation grilles on the external walls. These are protected from rain penetration by an overhanging floor slab with a down hanging fascia parapet. Vertical pivot windows and horizontal precast concrete ventilation slots at sill height allows for ventilation at the body level. These horizontal ventilation slots allow unobstructed airflow into the building even if the windows are closed. The original sketch shows openable windows below the window sill which would have allowed low level ventilation but they were not implemented because the structural beams got in the way. When windows are opened, especially on higher floors, papers sometimes fly around, making it hard to work. As a consequence, they left most windows closed.

**Analysis - strengths**

- Possibility to ventilate via monsoon window during monsoon rains.
- The heavy concrete slabs absorb direct solar radiation.
- Night ventilation mode to lower the structure during off hours.
- Rainwater can be collected.
- Use of prevailing wind direction.
- Easy maintenance of the windows
- The service cores as buffer zones
- Horizontal windows
- Volume to surface ratio

**Analysis – thoughts**

- The design is never tested in natural ventilation mode, nowadays the building uses HVAC system.
- The concrete overhangs are cold bridges.
With high winds the pivot windows needs to be closed.

Heavy concrete façade. Not applicable for a transformation of an existing office building.

Only use of cross-ventilation strategy.

Not possible to completely close the openings, rain water gets in with high winds.

Use of curtains to prevent glare has a negative influence on the natural ventilation.

Draft, papers are blown off the tables.

One Moulmein Rise, Singapore

An interesting detail has been used recently in a high-rise private apartment design at One Moulmein Rise, Singapore by Singapore architect firm WOHA that works well to regulate air flow and stop the rain from entering. With today’s advance mechanical and air-conditioning system and wide range of building materials, it is possible to use a mixed mode of natural and mechanical ventilation for the building during hot season.

3. Wind improved designs

Menara Umno, Indonesia

Wind wall

Liberty Tower of Meiji, Japan

The Liberty Tower of Meiji University is a high rise building at the centre of Tokyo Metropolitan area. The hybrid ventilation principle is based on natural ventilation for controlling the indoor climate in spring and fall seasons and a mechanical air-conditioning system in the rest of the year, when the outdoor air is not comfortable.

To enhance natural ventilation driving forces a "wind-floor" concept has been used. A central core is designed for utilization of the stack effect at each floor and above the centre core a wind floor is designed to enhance driving forces from the wind. On every floor there is air intake via perimeter counter units and exhaust through the opening at the top of the centre core. As the wind floor is open to four directions the driving force is expected to be stable through the year regardless of wind direction.

The system includes automatically controlled natural ventilation windows at night time, an automatic intake of outdoor air and wind floor outlets. Outdoor air intake control is
based on CO₂ and temperature sensors and is controlled via building management system. In the mechanical air-conditioning system the supplied air flow rate is controlled by a VAV system where the fresh air flow rate is automatically controlled based on indoor CO₂ concentration.

The use of the natural ventilation system reduces the cooling energy of the building considerably, ranging from 90% in April (spring) to a minimum of 6% in July (summer), and continues to reduce cooling to about 62% in November (autumn). The wind floor design on the 181 h floor, incorporating the automatically controlled ventilation windows on each of the other lower floors, increases the ventilation rate by 30% (Heiselberg, 2000).

Wind floor (all directions + ceiling ventilation)

4. Solar chimney

Edificio Hemiciclo Solar

https://es.wikiarquitectura.com/index.php/Edificio_Hemiciclo_Solar
The Tower at PNC Plaza

Manitoba Hydro Place

Natural ventilation in high-rise office buildings.
Appendix F. Extra

1. Daylight

Part of daylight research in Santiago de Chile done at the Catolica University at the Faculty of Architecture and Design in collaboration with Professor Claudio Vasquez.

Introduction

The Fondecyt (N° 1130815) project consist of a study in indoor environment and energy efficiency of office buildings in Santiago de Chile and is divided in energy and indoor environment. The indoor environment consist of measurement of incoming sunlight, a combination of artificial light and sunlight with lux measurements on workplaces, acoustics, photos have been taken to catch the light effectivity, and measurements for temperature, and humidity on three different heights (0.1m, 0.5m, 1.2m).

(Day) light

The investigation is partly still going on. A part of the investigation will be revealed in this report. The measurements in (day) light. Each week on of the offices has been monitored for 4 days, Thursday, Friday, Saturday and Sunday. Measurements during the weekend are been used for rectification of the measurements during office days.

At each offices several work places have been monitored, four times the same spots, to be able to compare results of different seasons. These spots count for a representation of all the workplaces in that office. The results can be used to give a general comment on offices. In some cases this can be difficult due cultural differences.

Focus

The focus of the light measurements in these offices is to compare the different offices in a general way, not to give comments on the way they construct in Chile. Chile is a country in development and people are used to different values and standards then in Europe.

Relevance

Design strategies may be of influence on the way we build. In case of floorplan versus daylight entrance and standards the Chileans can learn from other countries. By comparing the measurements with western norms, the government of Chile can apply new standards for Chile and its people.
Visual comfort

Visual comfort at workplaces has often been considered in terms of discomfort glare, luminance distribution and task visibility. Besides visual effects, the lighting environment has also impact on human physiology and behavior. Research has identified the benefits of daylight and sunlight in buildings for the health and wellbeing of occupants (Zelenay, 2011, p. 13). There are significantly less incidents of eyestrain reported by people whose workstations received large proportions of natural light (Osterhaus, 2005). Others suggest increasing evidence of direct links between the presence of daylight in working environments and productivity (Hellinga, 2013). A good view is highly desirable and preferable with foreground and the skyline. Occupants overestimate the amount of daylight that reaches their workstation from windows, even if they are far away from their workplace small windows can give a long way towards daylight and view connections. The design of a healthy daylight office is no guarantee for a better work experience (Osterhaus, 2005).

Glare

Daylight has a variety in intensity which gives it an additional challenge for the building environment. To create healthy and comfortable offices light needs to be taken into account in the design. Research reveals that serious problems may occur if there is an uncomfortable level of glare (IEA, 2010; Osterhaus, 2005).

The Illuminating Engineering Society of North America (IESNA) defines glare as “the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility” (Osterhaus, 2005).

There are two types of glare: disability glare and discomfort glare. Disability glare is the effect of light in the eye whereby visibility and visual performance are reduced. Discomfort glare is glare that produces discomfort. It does not necessarily interfere with visual performance or visibility. The difference between these two types may be better explained by using the German terms of physiological glare (instead of disability glare) and psychological glare (instead of discomfort glare). When discomfort glare is present, occupants may not notice any effect on their work performance at all. However, they might experience certain physiological symptoms such as headaches later on which could be attributed to their glare experience at work. When disability glare is present, occupants usually notice an immediate reduction in their ability to see or to perform a visual task. They might react by shifting their position or utilize any shading devices at their disposal, such as closing blinds or curtains. Sometimes both types of glare are present simultaneously. In such circumstances it can be difficult to separate the two effects from an assessment point of view, as current glare prediction methods utilize different formulae for each type.
Glare from windows usually arises when direct sunlight enters the room and shines into the eyes of occupants or reflects off visual tasks and surrounding surfaces. Alternatively, it may result from high window luminance, which is usually caused by sunlight reflections off exterior surfaces, for example the glazed facade of a building in the direct environment, or by a view of the sky. However, care needs to be taken to control the glaring effects of high luminance associated with the view of the sky. On the other hand, research found that discomfort glare from daylight appears to be tolerated to a much higher degree than predicted by available assessment methods if there is a pleasant view from the window causing the glare. These observations suggest that daylighting design has to be approached with care and a good understanding of the design parameters. Office layout relative to available exterior daylight openings and attention to the lighting of each task performed in the office thus become important factors in creating satisfactory working environments (Osterhaus, 2005).

**Luminance contrast**

In offices designed for frequent and prolonged computer use, windows continue to be a difficult problem to address. The increasing use of digital technologies in offices and industrial settings can create considerable challenges for workers in receiving, processing and transferring information in short periods of time. Eye movements between monitor screen, keyboard and manuscript can occur up to 30,000 times per day (Osterhaus, 2005). Often, a multitude of other visual tasks needs to be completed in addition to the screen-based work, and this in turn is likely to require different lighting criteria. To function properly and maintain a focused image, workers eyes have to adapt again and again to changes in luminance, contrast and distance to a visual object. If visual and ergonomic conditions are inappropriate, visual tasks, especially screen-based work, may quickly lead to complaints about difficulty focusing, double images, glare, or headaches. Muscular pain may add to these complaints when workers attempt to shift their posture in order to avoid perceived discomfort, for instance, reflections of a light source in the display terminal screen (Osterhaus, 2005).
Experts agree there is currently no commonly accepted holistic assessment system for lighting quality that predicts the effects of the luminous environment on building occupants. Current approach for assessing lighting quality as a recipe, implying that many ingredients contribute to an effective result.

Recommendations for the assessment of individual lighting quality components (discomfort glare, luminance distributions, etc.) published in lighting handbooks (IEA, 2010), standards and recommended practices predominantly address physiological factors, those that directly affect how we see. These are often treated in isolation. But indirect or psychological effects may occur because lighting can affect attention, motivation and behavior. While researchers are aware of these indirect effects, their study is at an early state of development. This inconsistency occurs in the uniformity of luminance as well. The physiological factor is focusing on optimal visual performance, where the psychological standpoint in the uniformity confirms the lack of inspiring environment in uniform environments (Zelenay, 2011).
Regulations

Luminance

*Luminance ratios*

The occurrence of glare depends not only on absolute luminance values, but also on relative luminance values and contrast, usually expressed by luminance ratios. Osterhaus identified three zones in the field of view of an occupant. The central zone, where the visual task takes place. The adjacent zone, the zone delimited by a cone of 60, and the non-adjacent zone, delimited by a wider cone of 120 degrees. Characterized by the ratios of 1:3:10 (Carlucci, 2015). The IENSNA uses the same ratios, only adding the ratio of 1:40, a contrast anywhere in the field.

*Table F.1 IENSNA recommended luminance ratio limits (Zelenay, 2011)*

<table>
<thead>
<tr>
<th>Part of view</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between paper task and adjacent VDT screen</td>
<td>3:1</td>
<td>1:3</td>
<td>30°</td>
</tr>
<tr>
<td>Between task and adjacent dark surroundings</td>
<td>3:1</td>
<td>1:3</td>
<td>30°-60°</td>
</tr>
<tr>
<td>Between task and remote (nonadjacent surfaces)</td>
<td>10:1</td>
<td>1:10</td>
<td>90°</td>
</tr>
<tr>
<td>Between points anywhere in the field of view</td>
<td>40:1</td>
<td>1:40</td>
<td>30°-90°</td>
</tr>
</tbody>
</table>

*Computer screens*

Average screen luminance for negative-contrast screens (screens with black characters on a white background) for newer VDTs with liquid crystal displays (LCDs) are close to 200 cd/m² (Zelenay, 2011). Based on this monitor luminance and a maximum luminance ratio of 1:10 for the binocular field of vision, the maximum desirable luminance of the window would be 2000 cd/m².

*Relaxation*

Relative brightness uniformity is generally desirable for physiological reasons, especially for adequate visual performance in office type settings, absolute uniformity from a psychological standpoint is not desirable as it can result in a lack of focus. Small areas exceeding the luminance ratios limits recommended by IESNA are “desirable for visual interest and distant eye focus for periodic relaxation throughout the day” (Zelenay, 2011, p. 15).
Discomfort

When the range of luminance in the visual field is too great, visual adaptation is disturbed and glare occurs (Luczak, Roetting, & Oehme, 2002, p. 193). There several glare probability predictions to predict the probability of glare in designs.

Daylight glare probability

Daylight glare probability (DGP) was developed by Wienold and Christoffersen. It is based on the vertical eye illuminance as well as on the glare source luminance, its solid angle and a position index. Compared to existing glare models, DGP shows a very strong correlation with the user’s response regarding glare perception (Suk & Schiler, 2012). For determining glare, the new DGP formula combines the vertical eye illuminance as a glare measure with the central term of existing glare indices. It also uses the part of the CIE-glare index, which describes the influence of the glare.

Daylight glare index

The index known as the Daylight Glare Index (DGI), is calculated based on source (e.g. window) luminance, source size, surround background luminance, and the location of the source relative to the occupant’s field of view. A number of studies have shown that there is a weak correlation between DGI and occupant response to glare due to the fact that the index does not account for the effect of view on occupant response to glare (Zelenay, 2011, pp. 29, 30). DGI has been an accepted standard for many years, research has demonstrated that its application can lead to unreliable results state that the glare perceived by observers under real sky conditions was less than predicted by the DGI equation (Osterhaus, 2005).

Visual comfort prediction

In addition to the daylight glare index, this problem also applies to the Visual Comfort Probability method as well and is due to the exponents for individual parameters in the various discomfort glare prediction formulae states that it is mathematically essential for additivity and sub divisibility of glare sources that the exponent for the solid angle of the glare sources is one. This finding was incorporated into the CIE glare index and the UGR systems.

CIE glare index

The CIE glare index (CGI) was developed by a technical committee of the International Commission on Illumination (CIE). Its formula is essentially split into two components, one describing the luminous environment of the room and the other describing the combined effect of luminance, size and position of the glare sources. It includes the glare source contribution to the adaptation of the observer in the description of the luminous environment of the room. The vertical illumination in the field of view includes the glare.
sources’ impact on a vertical plane at the subject’s eye and its adaption to the light (Linney, 2008).

Unified Glare Rating

Unified Glare Rating (UGR) system is developed for assessing glare from small artificial light sources. Therefore these glare index is not applicable to windows, because windows are considerably larger, allowing for greater adaptation of the eye and to higher acceptable luminance. Occupants are more tolerant for of glare from windows. Therefore the UGR can only be used for electrical lighting.

Table F.2 Degree of glare in different indices (Suk & Schiler, 2012).

<table>
<thead>
<tr>
<th>Degree of perceived glare</th>
<th>DGP</th>
<th>DGI</th>
<th>UGR</th>
<th>VCP</th>
<th>CGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperceptible</td>
<td>&lt; 0.35</td>
<td>&lt; 18</td>
<td>&lt;13</td>
<td>80-100</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Perceptible</td>
<td>0.35 – 0.40</td>
<td>18 – 24</td>
<td>13 – 22</td>
<td>60 – 80</td>
<td>13-22</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>0.40 – 0.45</td>
<td>24 – 31</td>
<td>22 – 28</td>
<td>40 – 60</td>
<td>22-28</td>
</tr>
<tr>
<td>Uncomfortable</td>
<td>&gt; 0.45</td>
<td>&gt; 31</td>
<td>&gt;28</td>
<td>&lt;40</td>
<td>&gt;28</td>
</tr>
</tbody>
</table>

Of the daylight glare prediction models, the DGP seems the most robust at present but all of the models have weaknesses (Veitch & Galasiu, 2012).

Illuminance

Vertical illuminance

Many of the glare indices which exist for the prediction of the likelihood of discomfort glare perception rely on specifying the ratio between the luminance of the glare source and the average background luminance. The average background luminance is defined as the luminance of all the other surfaces in the field of view with the glare source removed. However, many modern indices are now incorporating a function ‘Ev’ which is defined as the vertical illuminance on the plane the user’s eye is on. ‘Ev’ is a product of all the available light in the field of view which reaches the eye and therefore has a major impact on the adaptation levels of the eyes (Linney, 2008).
Conclusion

There doesn’t seem to be a lot of light engineering in the design of the offices. Although some offices score better than others, none of the offices scores sufficient for all the workplaces. The use of internal sun shading can be an influence on the visual comfort for the workplaces closer to the core of the building.

In workplaces next to the window values are sufficient to pass European norms, the offices further away and the offices with any access to daylight are below the 200 lux (Ev). The direct relation in illuminance and luminance is visible in the absence of glare. Only in two of the 72 workplaces a form of glare was detected.

Vertical illuminance scores are better when the internal sun shading is up. A better control on when the sun shading is up or down should be implemented to improve visual comfort, as well as replacement of internal artificial lightbulbs to increase the amount of lux in the field of view for workplaces further from the perimeter.

Advice for offices:

- Place other lightbulbs with more lumen
- Better internal sun shading control (saves electricity and improve visual comfort)
- Check if the light sources in the good position (effectiveness)

Further research:
Natural daylight

Daylight harvesting systems can be classified into two major categories – harvesting and transmitting daylight in its light form or converting and transmitting solar energy in electricity form. A very common example of converting solar power to electricity for transmission is Photo Voltaic Cells or Solar Cells which although are widely used. The intention is to explore the various existing solutions where daylight is collected and transmitted in its light form to use more effective daylight in the office.

Table 8.12 overview with daylight harvesting systems for cloudy days (Fontynont et al., 1999)

<table>
<thead>
<tr>
<th>Prismatic Panels</th>
<th>Light shelves</th>
<th>Light-Guiding Shades</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Prismatic Panels" /></td>
<td><img src="image2.png" alt="Light shelves" /></td>
<td><img src="image3.png" alt="Light-Guiding Shades" /></td>
</tr>
<tr>
<td>Prismatic panel is a saw tooth device functional in redirecting or refracting the incoming sky light. It redirects direct sun light but transmits the diffused light incident on surface, reducing glare substantially.</td>
<td>Light shelves mounted horizontally on window with pivot fixing and panels. It directs light to the ceiling by reflecting it from the panels and illuminates the room.</td>
<td>Light-guiding shades redirects the sky light to ceiling by the usage of deep external shading with two reflecting surfaces and a diffusing glass element which makes possible the transmittance of diffused light into the building.</td>
</tr>
</tbody>
</table>

Guiding Glass with Holographic Optical Elements

Zenithal light-guiding glass redirects the zenithal zone day light to the building by a polymeric film with holographic diffraction grating.

Anabolic Ceilings

Anabolic ceiling has external installation of parabolic collector and light directing duct with reflective lining, transmitting daylight to remote areas of room and dispersing by parabolic reflector at exit aperture.
Lenses can capture oblique light and concentrate this on a certain surface. Arzon Solar is using economical but effective acrylic polymethyl methacrylate (PMMA) Fresnel lenses to collect sunlight, concentrating it up to 500 times onto small and highly efficient advanced PV solar cells (or on the light collector).

Fresnel lens design allows construction of lenses of large aperture and short focal length without the mass and volume of material required by a conventional lens. When the teeth run in straight rows, the lenses act as line-focusing concentrators. When the teeth are arranged in concentric circles, light is focused at a central point. However, no lens can transmit 100 percent of the incident light. The best that lenses can transmit is 90 to 95 percent, and in practice, most transmit less.

In a conventional collector the amount of collected daylight will not increase if the height of the chimney increases. With the light getting absorbed by the black body of the walls of the solar chimney, light will get lost for lighting purposes. Lenses can optimal collect the daylight on cloudy days. For the light collector this means a greater input of natural daylight, which will give a greater light density in the office. In the sketch is visible that the direct access of natural light is depending on the size of the openings.
Figure 8.9 cross section of solar chimney light collector (Left) with effective solar collector area (dotted line). Solar chimney in combination with lenses where more light can be collected (Right).
III. REFERENCES


Borisuit, A. (2013). The impact of light including non-image forming effects on visual comfort. ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE.


ebrary [http://site.ebrary.com/id/10206495](http://site.ebrary.com/id/10206495)


ebrary [http://site.ebrary.com/id/10206495](http://site.ebrary.com/id/10206495)


Technologies for Sustainable Built Environment Centre, Henley Business School, Oxfordshire, UK.


and Environment, 65, 109-117.
doi: http://dx.doi.org/10.1016/j.buildenv.2013.03.022
IV. CURRICULUM VITAE

- Jasper (Jacobus Pieter) Overduin
- Nationality: Dutch
- Birthday: 07-07-1990
- Age: 25

Education

- Master Building Technology, Faculty of Architecture, Delft University of Technology, Sep. 2013 – June 2016, with 7 months break for internship in Chile.

Practices

- Solar Decathlon Team TU Delft, sponsoring and partners, building management, Sep. 2013 – Aug. 2014, 12 months (0.4 fte). Worldwide competition with 20 teams. Designing and building an innovative passive house in Versailles, Paris, France. Challenge to attract partners and sponsors for financing the project. Estimated costs needed to be sponsored € 800,000. We succeeded within 5 months. Responsible for: Logistics for building the wooden skeleton, the solar systems and the installations.

Extra Curriculum

Skills


*Languages:* Dutch (native), English (expert), Spanish (advanced), German (3 years high school, close to Dutch).

*Multi(disciplinary) teams:* Working in small teams makes me work more effective. Continuously questioning the design, opening new insights, resulting in better design. With the Solar Decathlon I’ve worked within a team of 30 students from different faculties. Convincing students to make the design works in the best way.

**Personal profile**

Peers characterized me as: entrepreneur, great responsibility, accurate, creative, analytic, able to judge fast and honest, adventurous, sportive and helpful.

**Experience abroad**

- Santiago de Chile, practice (see practices above), learning Spanish and cultural experience. Feb. 2015 – Aug. 2015 (7 months).

**Secondary activities**

- BT Series, a lecture series organized for the master student organization BouT. From professional to student. A sequel of lectures, 5 speakers each time, exposing and showing the real life implementation of Building Technology. Organized the first lecture and arranged a network of professionals for the following lectures. Event date 11 November 2014.
- Sanctus Virgilius video committee, editor, May 2012 – Aug. 2012, 4 months (0.5 fte). Promotion video’s for new students at the University of Delft. Filming and editing during the introduction week of the TU Delft.
- S.V.V.V. Taurus lustrum committee, president, May 2011 - June 2012, 13 months (0.3 fte). Organizing several activities for Taurus, student football club in Delft (250 members).

**Experiences**

- Deerns Consulting engineers in Rijswijk, junior engineer, healthcare department, Dec. 2015 – Mar. 2016. Set-up for an energy benchmark for hospitals and supporting tasks (0.3 fte).
Details

During my bachelor I’ve always been curious about facades, during my masters I’ve been studying the behaviour of Phase Change Materials and Algae facades. Using the façade as energy buffer/generator has been done in nature ever since we can imagine. Using the knowledge and new techniques are the challenges for architecture.

During projects I can focus on certain parts, this is what separates me from architects. Drive for technology, trying to optimize certain details and challenging the design.
FAÇADE FOR WIND AND STACK DRIVEN VENTILATION IN TROPICAL HIGH-RISE OFFICE