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Master Thesis

Potentials and limitations of high-rise office buildings for meeting energy standards in temperate climates: Early-Stage Design Guidelines for Architects

carried out for the purpose of obtaining the academic degree of Diplom-Ingenieurin (Dipl.-Ing. or DI), submitted to the Vienna University of Technology, Faculty of Architecture and Spatial Planning, by

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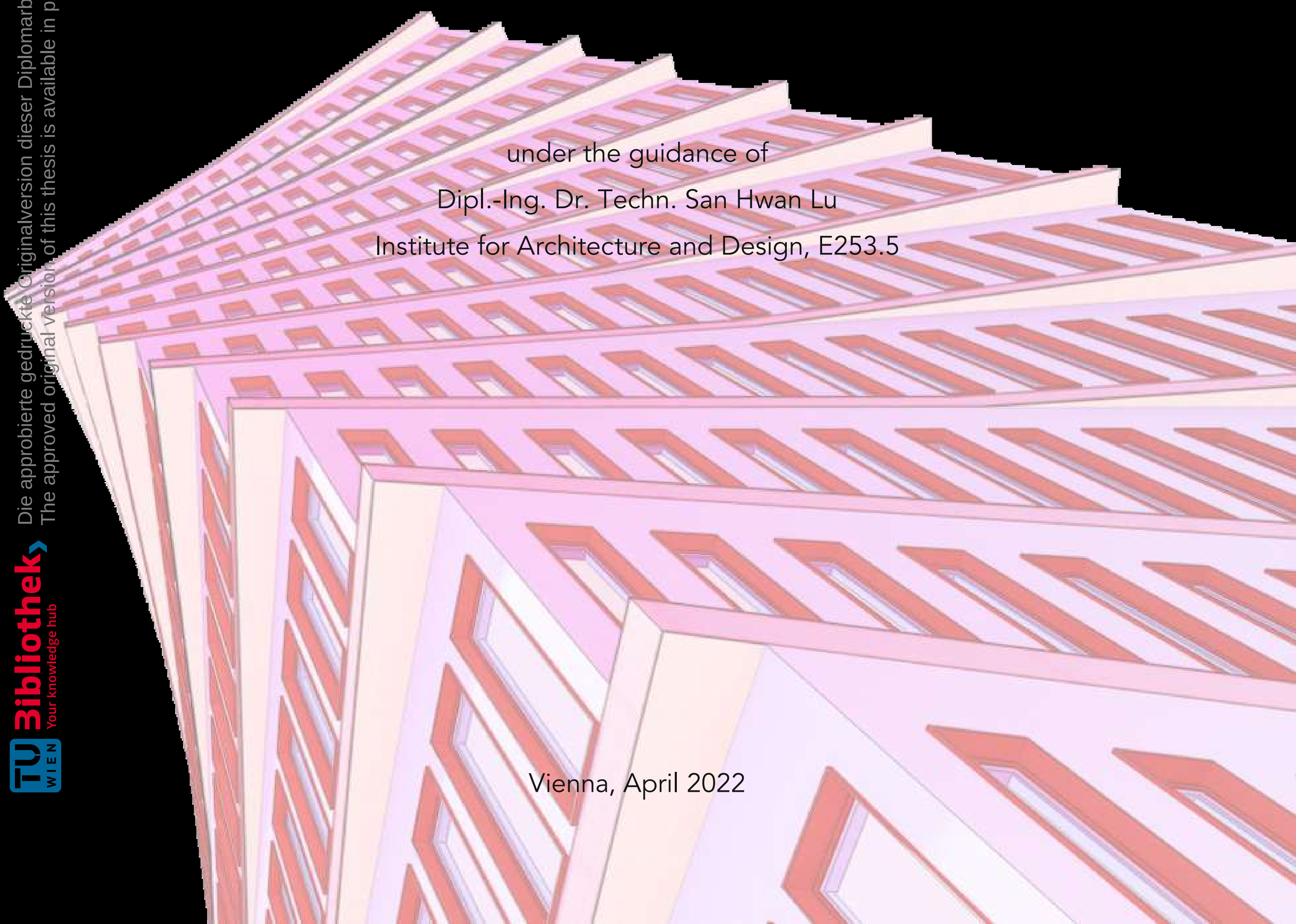

under the guidance of

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Institute for Architecture and Design, E253.5

Vienna, April 2022

ABSTRACT

[English]

Over the last decades, high-rise buildings have become increasingly popular, cropping up as symbols of wealth and prosperity in global cosmopolitan cities. However, despite the socio-economic benefits associated with tall buildings, the high-rise typology tends to be more energy intensive than low-rise buildings, having a significant impact on the environment. Under the effect of global warming, there has been worldwide pressure regarding the environmental performance of tall buildings.

As of 2020, the Romanian building sector, including high-rises, needs to comply with strict energy efficiency regulations which set a limit on the primary energy usage, CO_2 emissions and the amount of renewable energy generated on site. Meeting these energy thresholds becomes less feasible when aiming for a considerable building height due to higher wind velocities, more direct sunlight and lower air temperature, which can have a significant effect on the indoor environment and total energy demand.

This study examines the potential of an office high-rise building located in Romania, to meet the energy thresholds introduced in 2020. The aim of this research work is to define to what extent energy regulations are a limitation to the construction of high-rise office buildings in Romania and what changes can be proposed by means of design parameters in order to reach the desired height and the required energy output. By undergoing extensive parametric thermal simulations, this research explores via variations in building height, building orientation, shape and window-to-wall ratio, where the height threshold for office high-rise buildings lays until energy regulations are no longer satisfied. With a computational methodology of work, using parametric modeling in Grasshopper, the impact of the different design scenarios is evaluated based on the primary energy output.

This study aims to serve as a tool for Architects and Engineers to analyze the high-rise performance of tall buildings in parallel to the height increment. The outcome provides a gap filling knowledge of the relationship between the selected design parameters, their impacts on one another, and the building performance of the various design scenarios.

Focus and Restrictions

Passive design strategies for energy efficient office high-rises, building energy optimization with parametric simulations, energy regulations for office buildings in Romania.

KURZFASSUNG

[Deutsch]

In den letzten Jahrzehnten ist die Hochhaus Typologie weltweit immer beliebter geworden und steht heute als Symbol für Wohlstand und Reichtum in Weltstädten. Trotz der sozioökonomischen Vorteile, die mit Hochhäusern verbunden sind, sind Hochhäuser in der Regel energieintensiver als Flachbauten, was erhebliche Auswirkungen auf die Umwelt hat. Unter dem Einfluss der globalen Erwärmung ist die Energieeffizienz von Hochhäusern weltweit umstritten.

Ab 2020 muss der rumänische Bausektor, einschließlich der Hochhäuser, strenge Energieeffizienzvorschriften einhalten, die den Primärenergieverbrauch, die CO2-Emissionen und die Menge der vor Ort erzeugten erneuerbaren Energie begrenzen. Die Einhaltung dieser Energiegrenzwerte ist schwer erreichbar, wenn eine erhebliche Gebäudehöhe angestrebt wird, da höhere Windgeschwindigkeiten, mehr direkte Sonneneinstrahlung und niedrigere Lufttemperaturen wesentliche Auswirkungen auf das Innenraumklima und den Gesamtenergiebedarf haben können.

Diese Studie untersucht das Potenzial eines Bürohochhauses in Rumänien, die im Jahr 2020 eingeführten Energiegrenzwerte zu erfüllen. Ziel dieser Forschungsarbeit ist zu bestimmen, inwieweit Energievorschriften den Bau von Bürohochhäusern in Rumänien einschränken und welche Änderungen an Entwurfsparametern vorgeschlagen werden können, um die gewünschte Höhe und den maximal zulässigen Energieverbrauch zu erreichen. Anhand von parametrischen thermischen Simulationen wird über Variationen der Gebäudehöhe, der Gebäudeausrichtung, der Gebäudeform und des Fensteranteils untersucht, wo die Höhenschwelle für Bürohochhäuser liegt, bis die Energievorschriften nicht mehr erfüllt werden können. Die parametrische Modellierung wird in Grasshopper aufgebaut, und die Auswirkung der verschiedenen Entwurfsszenarien wird basierend auf dem Primärenergiebedarf bewertet.

Durch die Darlegung der gegenwärtigen Beziehung zwischen den ausgewählten Entwurfsparametern, ihre Auswirkungen aufeinander und die Gebäudeleistung der verschiedenen Designszenarien, zielt diese Studie Wissenslücken über die Energiezunahme mit der Höhe zu füllen und soll Architekten und Ingenieuren als Werkzeug dienen, um die Leistung von Hochhäusern parallel zum Höhenzuwachs zu analysieren.

Fokus und Einschränkungen

Passive Entwurfsstrategien für energieeffiziente Bürohochhäuser, Gebäudeenergieoptimierung anhand parametrischer Simulationen, Energievorschriften für Bürogebäude in Rumänien.

Statutory declaration

I declare in lieu of oath that the present work was prepared by me independently in accordance with the recognized principles for scientific treatises. All aids used, in particular the literature on which they are based, are named and listed in this work. The passages taken verbatim from the sources are marked as such.

So far, I have not presented the topic of this work to an appraiser for assessment in any form as an examination paper, either at home or abroad. This work agrees with the work assessed by the assessors.

I acknowledge that the submitted work will be checked electronically and technically with suitable and state-of-the-art means (plagiarism detection software). On the one hand, this ensures that the high quality standards within the framework of the applicable rules for safeguarding good scientific practice "Code of Conduct" at the Vienna University of Technology were observed when preparing the submitted work. On the other hand, a comparison with other student theses prevents violations of my personal copyright.

Location, Date
Vienna, April 2022
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Signature
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Acknoledgements

First of all, I would like to express my sincere gratitude to my mentor, Dipl.-Ing. Dr. Techn. San Hwan Lu for imparting his knowledge on energy efficient architecture, as well as for challenging me throughout this process. Special thanks go also to my family and my boyfriend for always keeping me motivated throughout my study years. Your continuous support and advice were more valuable to me than you could ever imagine.

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ACRONYMS

BCR — **Building coverage ratio**
percentage rate of the building area divided by the overall site area

COP — **Coefficient of performance**
indicator for the heating efficiency

EEF — **Energy efficiency ratio**
indicator for the cooling efficiency

FAR — **Floor area ratio**
also referred to as the FSI, is the total built-up area of the building divided by the plot area

FSI — **Floor space index**
also referred to as the FAR, is the total built-up area of the building divided by the plot area

GFA — **Gross floor area**

NFA — **Net floor area**

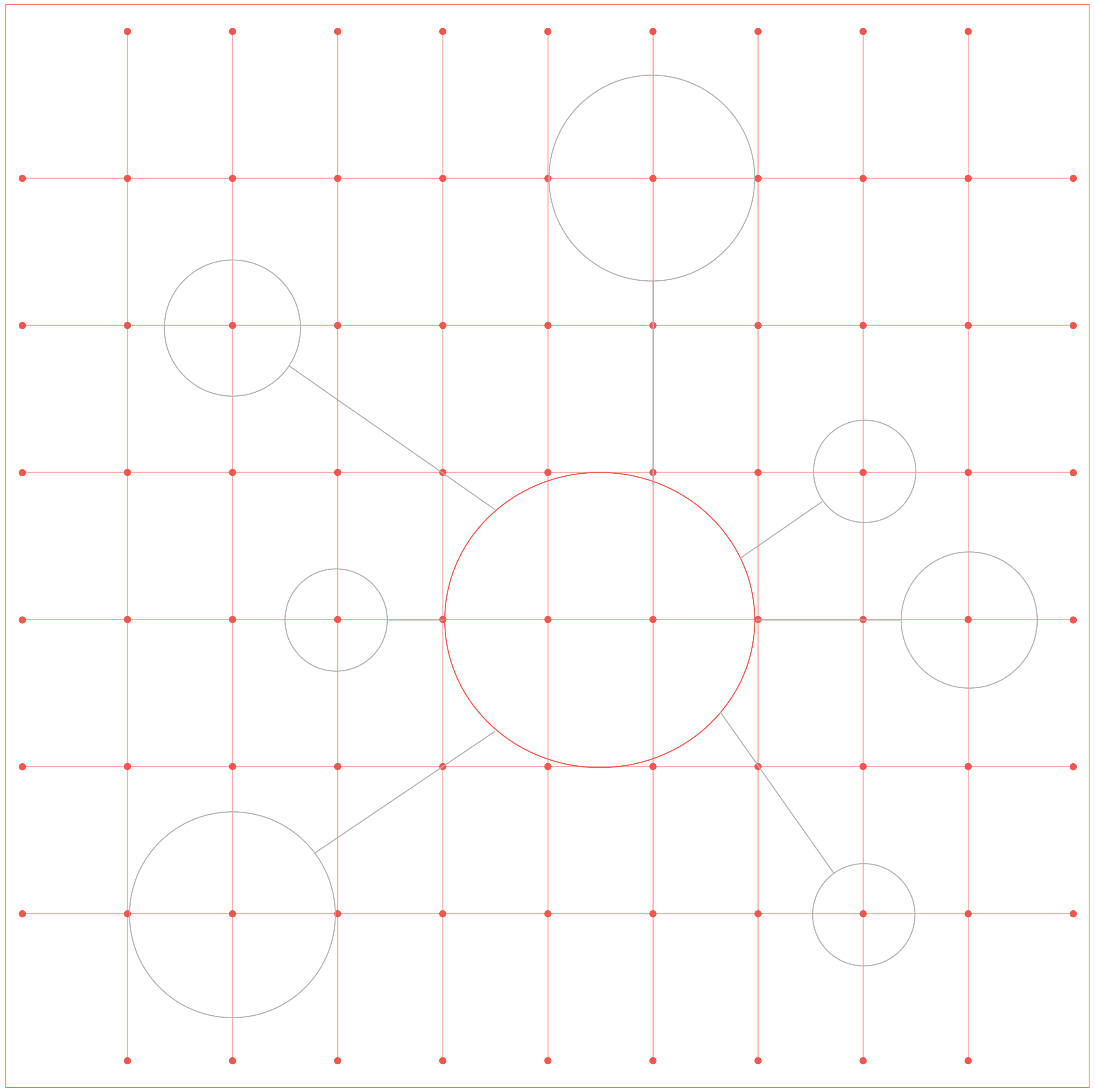
PPD — **Predicted Percentage of Dissatisfaction**
quantitative measure of the thermal comfort level by Fanger, indicating the percentage of people feeling dissatisfied by certain thermal conditions

PPV — **Predicted Mean Vote**
comfort index by Fanger ranging from -3 to +3, describing the feeling of cold to hot based on six variables: air temperature, air velocity, relative humidity, mean radiant temperature, clothing insulation and metabolism rate

SR — **Slenderness Ratio**
aspect ratio, i.e., the quotient between the height and the width of a building (for round buildings, the radius is considered as the width of the building)

SF — **Shape Factor**
indicator of a building`s compactness, also known as the Ag/V – Ratio, which represents the quotient between the envelope area (Ag) and the heated volume (V)

WWR — **Window to wall ratio**



Research Framework 1

1.1 BACKGROUND

To date, 4 billion people live in cities and by 2050, this number is expected to reach 6 billion. This densification of urban areas is expected to have a dramatic impact on climate change, on one hand because of the heat island effect and on the other hand because of the increased demand in resources. Already today, the building sector uses 35% of the global resources, 40% of the total energy, consumes 12% of the world's drinkable water and produces almost 40% of global carbon emissions *(Saint-Gobain, 22 August 2017)*.

In order to deal with the inevitable effects of global warming, building regulations concerning energy use were introduced globally. In Europe, there are two main legislative instruments on the energy performance of the EU building stock, the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive. By introducing these two Directives, the Union's main objective is to reduce greenhouse gas emissions by 85%-90% by 2050 in order to maintain the global temperature rise below 2°C, with respect to the Paris Agreement on climate change from December 2015. Member states needed to transpose these Directives into National Legislation by 2020 and establish a long-term strategy on how to improve the energy efficiency of the building stock *(European Commission, 2014)*.

1.2 PROBLEM STATEMENT

Meeting future energy requirements can be quite challenging for certain building typologies, like high-rise buildings. Today, the desire for verticality is high given the effects of densification, i.e., urbanization and the socio-economic advantages that tall buildings bring with them *(Gonçalves & Umakoshi, 2015)*. Over the last decades, high-rise buildings have become increasingly popular, cropping up as symbols of wealth and prosperity in global cities. Nowadays, high rise buildings are spreading more and more across the globe, the total number of 200m+ buildings reaching 1,733 in 2020, marking a 561% increase from the year 2000, when only 262 existed *(CTBUH, 2020)*. According to *CTBUH (2020)*, 36% of the 100 tallest buildings worldwide are office-only high-rise buildings, 49% are mixed use, 11% are residential and 4% are hotel-only.

According to *Godoy-Shimizu et al. (2018)*, there is a direct proportional relationship between building height and energy consumption, i.e., the higher we aim, the bigger also the energy demand per square meter. A 10-story high-rise building uses 77% more electricity and 20% more fossil fuel compared to a low-rise building of 5 stories, translating into a gradual increase in CO_2 emissions of 2.4% and 2.9% respectively for each additional storey *(Godoy-Shimizu et al., 2018)*.

Romania has implemented some energy thresholds to regulate the energy consumption of the building sector. As of 2020, all new buildings should comply with 3 energy indicators – a requirement for the maximum primary fossil energy consumption, a maximum amount of CO_2 emissions and a minimum amount of renewable energy generated on site. These new energy benchmarks also apply for high-rise buildings, but meeting these energy thresholds becomes less feasible the higher a building is.

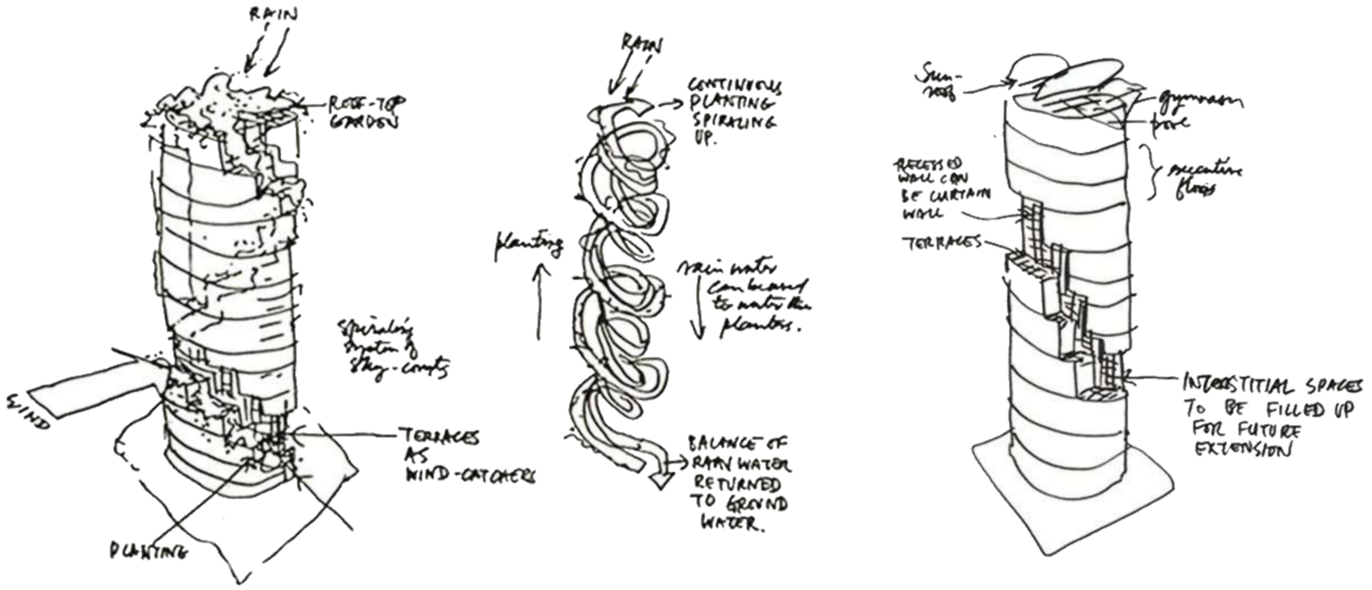


Figure 1.1: Ken Yeang, diagrammatic sketches of Menara Mesiniaga, Petaling Jaya, Malaysia, 1992
Source: Solaripedia (n.d.)

1.3 RESEARCH QUESTION

This study examines the potential of an office high-rise building located a temperate climate, respectively Romania, to meet the energy thresholds introduced in 2020. By taking into account variations in design parameters, i.e., building height, orientation, shape and window-to wall ratio. The aim of this research is to answer the following research question:

"To what extent are energy regulations a limitation to the construction of a high-rise office building in Romania and which changes can be proposed by means of parametric optimization in order to reach the desired height and the required energy output?"

In order to be able to answer this main research question, a number of secondary questions will help achieve the research goal:

SQ.1. How does the core to usable floor area ratio change with height?

SQ.2. How does the energy efficiency of office high-rises change in relation to the addition of floors and how does that affect the energy indicators?

SQ.3. What optimizations can be proposed in terms of orientation, shape and window-to-wall ratio in order to improve the energy efficiency and achieve the desired height?

SQ.4. Is there a relationship between compactness and window-to-wall ratio?

SQ.5. Where lies the height threshold for office high-rise buildings until energy regulations are no longer satisfied?

1.4 METHODOLOGY

This paper examines to what extend building design may affect the thermal performance of an office high-rise building located in a temperate climate. By undergoing extensive parametric thermal simulations, this research explores via variations in building height, building orientation, shape and window-to-wall ratio, where the height threshold for office high-rise buildings lies until energy regulations are no longer satisfied.

The research design for the present study involves the following steps. First, data and information about passive design strategies, indoor comfort and energy regulations is gathered and analysed through the literature review. In order to ensure a certain viability of the reviewed literature, only publications from 1990 to 2021 are considered, without setting any language limitations. A complete list of the databases searched is provided in the *Appendix*. The selected sources are mainly books and journal articles, but also European and national energy policies.

In the second part of the paper, the energy benchmarks and most influential building parameters are being identified, which will serve as input variables for the thermal simulations. The benchmarks are based on the outcome of the reviewed literature, building regulations and thermal comfort considerations. Following from the analysed literature, four different plan layouts are being selected, three window to wall ratios, as well as a maximum building height and the orientation angles at which the application phase of this research is being conducted.

The energy performance simulation will be set up in Grasshopper. The plug-ins Honeybee and Ladybug, hence EnergyPlus and Daysim, will be used to assess the influence of the selected parameters on the overall energy performance and thermal comfort. A local sensitivity analysis is performed by changing one design parameter at the time, while the others remain constant. The results of this optimization process will be evaluated in terms of energy performance and thermal comfort at two different building levels, at the 2nd level (4.2m height) and at the last but one level. Using Colibri Iterator, the performance of all possible parameter combinations is assessed and the results are compared using Microsoft Excel and Design Explorer.

This workflow serves as a tool to analyse the high-rise performance in parallel to the height increment. The outcome provides a gap filling knowledge of the relationship between the parameters, their impacts on one another, and the building performance.

2 Literature Review

2.1 DEFINING "ENERGY EFFICIENT"

The EU Building Efficiency Directive imposes that from 2020 all new buildings should have a significantly low energy requirement. In addition to the Passive House Standard (PHS), Nearly-Zero Energy Building (nZEB) concepts are considered in order to achieve this goal. It is often believed that nZEBs no longer require any energy, but this is not the case. Their total energy consumption represents the total energy drawn from the grid and the renewable energy fed into the grid. As a result, nZEBs are particularly energy-efficient buildings with large scale energy generating systems. However, buildings with a higher number of floors are disadvantaged in this sense, because the application of certain energy generating systems, such as photovoltaics, is limited to a small area of application. With that in mind, the urban, architectural and building technology design needs to happen in an intrinsic matter, as a response to the regional and urban climate conditions, in order to reduce the energy demand as much as possible.

This study will be carried out in a temperate climate, using the climate data of Sibiu, Romania as reference. Like all the other countries of the EU, the Romanian building sector needs to comply with 3 energy indicators – a requirement for the maximum primary fossil energy consumption, a maximum total amount of CO_2 emissions and a minimum amount of renewable energy generated on site. *Table 2.1* indicates the maximum allowable primary energy and the maximum amount of CO_2 emissions for different clime zones. A minimum amount of renewable energy of 30% is required for all climate zones. Our city of study is located in climate zone 3, corresponding to a maximum allowable primary energy need of 86kWh/m^2.year and 9,9kg/m^2.year of CO_2 emissions. These energy benchmarks also apply for high-rise buildings, but meeting these energy thresholds becomes less feasible when aiming for a considerable building height.

Figure 2.1: Climate Zones of Romania

Table 2.1: Energy thresholds for office buildings in Romania, 2021
Source: Metodologie de calcul al performantei energetice a ... (2021, p. 72)

Climate Zone	Primary Energy Use kWh/m²․year	CO2 emissions kg/ m²․year	Share of renewable energy %
I (-12 °C)	83.0	8.9	30
II (-15 °C)	86.0	9.5	30
III (-18 °C)	86.0	9.9	30
IV (-21 °C)	87.0	10.6	30
V (-25 °C)	88.6	11.2	30

2.2 DEFINING "THERMAL COMFORT"

Thermal comfort Is defined by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) as:

'That state of mind which expresses
satisfaction with the thermal environment'
(*ASHRAE, 2009*).

Thermal comfort is perceived differently by any person and is highly influenced by behavioral, physiological as well as psychological factors.

Thermal comfort standards are evaluated worldwide based on Fanger's Predicted Mean Vote, in short PMV, and Fanger's Predicted Percentage of Dissatisfaction, in short PPD. The PMV-index is based on the seven-point thermal sensation scale proposed by ASHARE and can take values from +3 to -3, where hot, warm, slightly warm, neutral, slightly cool, cool and cold correspond to the scales of comfort -3, -2, -1, 0, +1, +2 and +3. For new buildings, the PMV-index should range between -0.5 and +0.5. In addition, the PPD needs to be less than 10% in order to perceive the indoor conditions as comfortable *(Table 2.2)*.

According to the European Standard *EN15251: 2007*, different categories of PPD and PMV are provided in relation to 6 thermal parameters (clothing, activity level, air and mean radiant temperature, air velocity and humidity). *Table 2.4* shows reasonable values for the parameters which influence the PMV and PPD. These values will be used later as input values for the simulation parameter study, in order to achieve a pleasant indoor comfort level.

In addition, the European Standard *EN15251: 2007* sets limits for the maximum and minimum comfortable indoor temperatures to ensure that the implemented European regulations on the energy efficiency of buildings do not undermine the comfort level of the occupants. The European Standard *EN15251: 2007* recommends a range of temperature for a comfortable indoor environment of minimum heating set point of 20°C and a maximum cooling set point of 26°C for open office layouts under a normal level of expectation. However, for this study we aim for a high degree of comfort, which is why the minimum heating setpoints for category I will be used later as input values for the simulation parameter study *(Table 2.5)*.

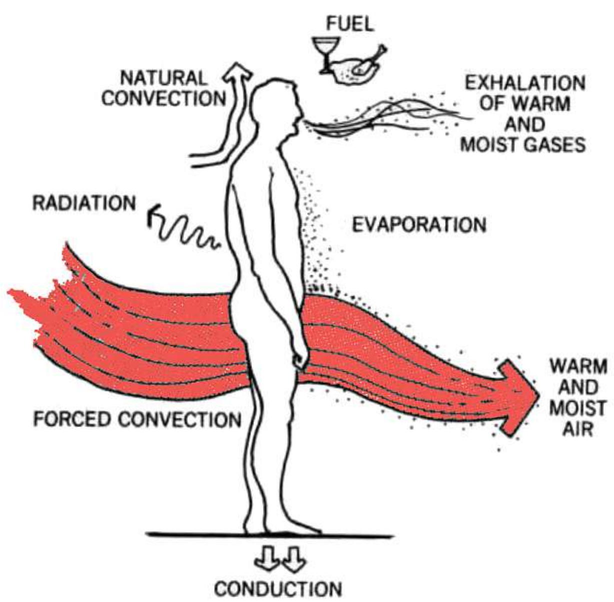


Figure 2.2: Methods of dissipating waste heat from a biological machine.
Source: Lechner, 2015

Table 2.2: Examples of recommended categories for design of mechanical heated and cooled buildings
Source: EN 15251, 2007

Category	Thermal state of the body as a whole	
	PPD %	Predicted Mean Vote PMV
I	< 6	-0.2 < PMV < +0.2
II	< 10	-0.5 < PMV < +0.5
III	< 15	-0.7 < PMV < +0.7
IV	> 15	PMV < -0.7 ; or +0.7 < PMV

Table 2.3: Description of the applicability of the categories used
Source: EN 15251, 2007

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Table 2.4: Recommended indoor temperature for building design and ventilation system for a lanscaped office floor plan, category II
Source: EN 15251, 2007

Season	Clothing level clo	Metabolic rate met	Air velocity m/s	Ventilation Rate l/s, m²	Maintained luminance lx	Occupancy m²/person
Summer	1.0	1.2 (sedentary)	15	0.5	500	15
Winter	0.5	1.2 (sedentary)	15	0.5	500	15

Table 2.5: Recommended indoor temperature for building design and ventilation system
Source: EN 15251, 2007

Type of building/ space	Category	Min. for heating (winter season) ~1.0 clo	Min. for cooling (summer season) ~0.5 clo
Landscaped office (open plan office) Sedentary ~ 1,2 met	I	21.0 °C	25.5 °C
	II	20.0 °C	26.0 °C
	III	19.0 °C	27.0 °C

2.3 DEFINING "HIGH-RISE"

Tall buildings were an iconic typology of the urban fabric of New York and Chicago as early as the 1920s and 1930s. It was only after World War II that tall buildings began to appear in Europe, Asia, and the Middle East in response to the shortage of housing and in order to create business and financial districts. However, the residential buildings that emerged at that time were rather associated with low-quality construction and poor living conditions. On the other hand, office buildings have become very profitable and were considered representative symbols of power and national wealth.

The first so called "skyscraper" is considered to be The Home Insurance Building in Chicago, built in 1885 after the invention of the elevator in 1883, exceeding the 5-storey threshold, with its 42m height, i.e., 10 storeys. At the beginning of the 20th century, a new limit was set at 20 stories, and this was considered for decades as being the definition of a tall building in North America and Europe *(Gonçalves & Umakoshi, 2015)*.

Today, tallness isn`t defined anymore by the number of storeys alone, but also by the proportions of the building, by the height of the surrounding buildings, and whether or not "tall building technologies" are integrated, such as vertical transportation, wind bracing etc. The Council on Tall Buildings and Urban Habitat *(CTBUH)* also sets a numeric threshold of 14 storeys/50m that defines a building as being tall, hence a high-rise building. However, a 14-storeys building might not be considered as being a high-rise building in a high-rise city like Chicago. The building proportions are also a defining criterion, because a building might not appear tall due to its large footprint area.

Taking the aforementioned criteria into account, i.e., context, building proportion and integrated technologies, buildings which exceed the 50m threshold can be considered as being tall, buildings above 300m are identified as supertall buildings, and those above 600m as megatalls *(CTBUH, n.d.)*.

Considering these definitions of tallness, the present study considers a building lower that 300m, but higher than 50m, with a minimum slenderness ratio of 1:2 as defining criteria for a high-rise building.

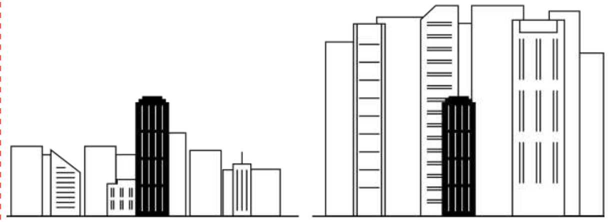


Figure 2.3: Height relative to context
Source: CTBUH, n.d

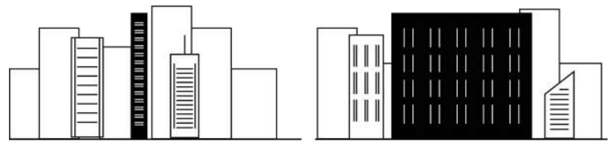


Figure 2.4: Height relative to proportions
Source: CTBUH, n.d

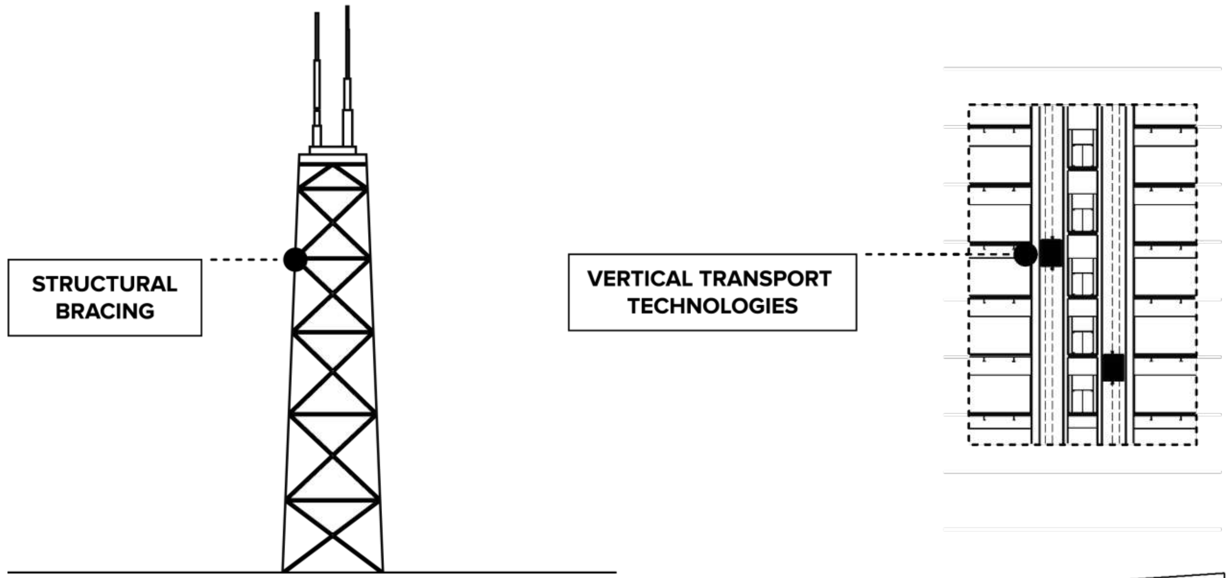


Figure 2.5: Tall building technologies
Source: CTBUH, n.d

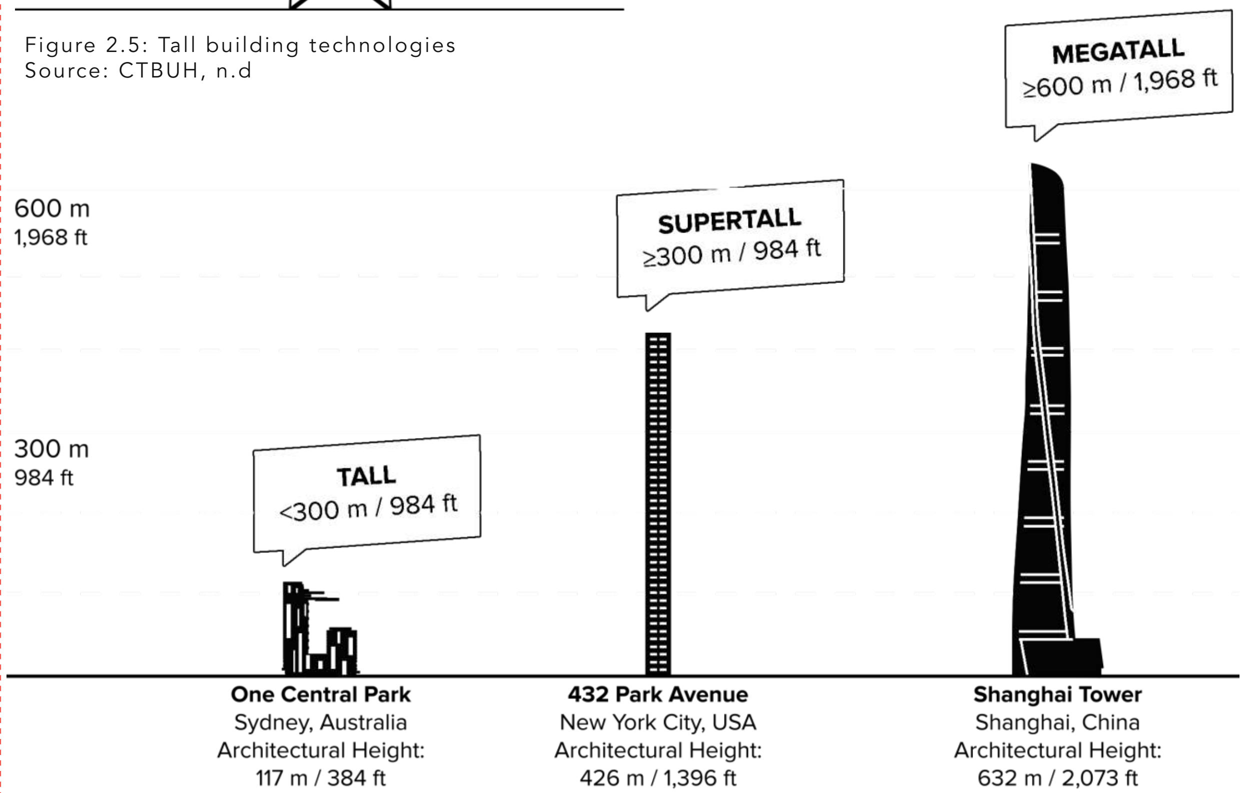


Figure 2.6: Classification of the buildings by their height
Source: CTBUH, n.d

2.4 HIGH-RISE CHARACTERISTICS

The performance of the building on energy efficiency is highly influenced by certain geometric characteristics, such as orientation, building height, shape and window to wall ratio, all which need to be designed in such way to be able to withstand the climate conditions of the site. Tall buildings are more susceptible to external environmental factors than low rise buildings. Architects and engineers need to take into account higher wind velocities, more direct sunlight and lower air temperatures, all which can have a significant effect on the indoor environment and total energy demand of high-rise buildings.

SOLAR LOADS

Solar radiation has a big impact on the energy performance of buildings. Especially tall buildings allocate big amounts of heating, cooling and lighting loads, which can be reduced by adopting environmentally sustainable design principles. The orientation of the building, shape and design of the envelope are essential parameters that can determine the amount of incoming daylight, respectively solar radiation throughout the year.

Hight is another variable that needs to be accounted for in high-rises. The upper levels of high-rise buildings are exposed to more direct sunlight and slightly lower air temperatures, with a decrease in temperature of -1 °C per 100m *(Wood, 2018)*. The degree of exposure to solar radiation can be managed by means of orientation, shape and facade parameters, such as window to wall ratio and shading elements.

WIND LOADS

High-rises are subjected to significant wind velocities, which have a great impact on the structure and the amount of structural material required to withstand these loads. Several studies by *Bottema (1993)* and *Tsang et. al (2012)* proved that building height has significant effects on high-rises by creating wind-flow areas. *Bottema (1993)* describes the wind patterns around a tall building and demonstrates an increase of wind speed with height:

$$v = v_{ref} * \ln(h/z_0) / \ln(h_{ref}/z_0) \qquad [2.1]$$

v = wind speed at height z above ground level
vref = reference speed, i.e., a wind speed we already know at height zref
h = height above ground level for the desired velocity, v
href = reference height, i.e., the height where we know the exact wind speed
z0 = roughness length in the current wind direction (a roughness class of 3.5 refers to a large city with many trees and buildings)

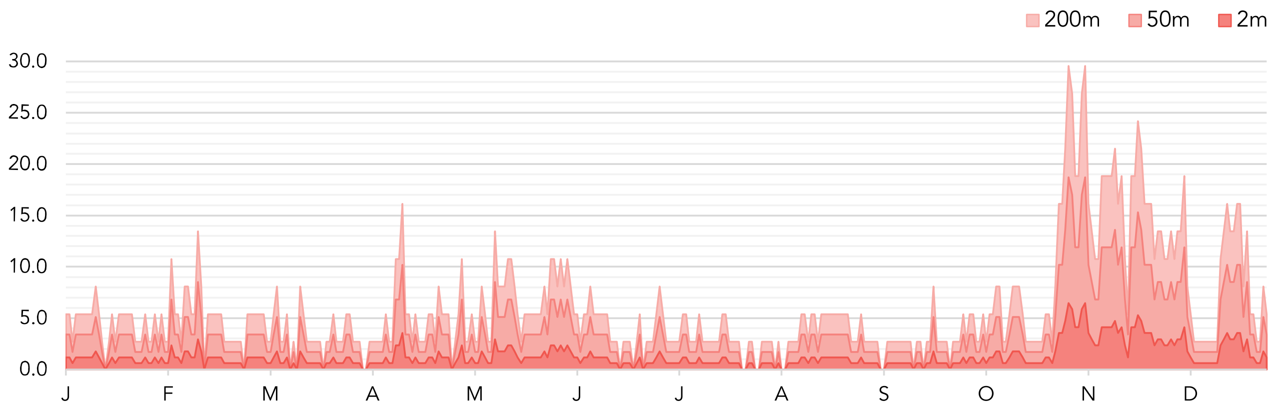


Figure 2.7: Wind speed at 2m, 50m and 200m (Sibiu, Roamnia)
Source: Grasshopper Ladybug Windspeed Calculator Component

2.4.1 ORIENTATION

The orientation of the building determines the amount of sun exposure on different envelope surfaces, hence it can minimize the need for artificial lighting, reduce heating and cooling loads and affect the visual comfort of the occupants. Cooling loads account for the highest proportion of energy demand in office buildings. Therefore, the building must be shaped and orientated in a way to reduce its exposure to solar radiation.

According to *Raji et al. (2017)*, a rotation of 0° from the north is the ideal orientation in terms of energy efficiency, regardless of climate. On the contrary, a 90° rotation from the north is the least efficient orientation for plan aspect ratios between 1:2 to 10:1 with an equiangular four-sided plan shape.

The same study points out that orientation needs to be defined together with shape and window-to-wall ratio. Elliptical buildings, do not allow to have a specific orientation, while more elongated shapes allow to orientate the building towards a specific axis.

Figure 2.8 shows the difference in total energy use between different orientations for a square and a rectangular plan layout in a temperate climate. It can be deduced that buildings oriented along the east-west axis prevent solar loads in the early morning or afternoon, which results in the lowest energy consumption, while the highest amount of energy consumption is reached by buildings oriented along the north-south axis.

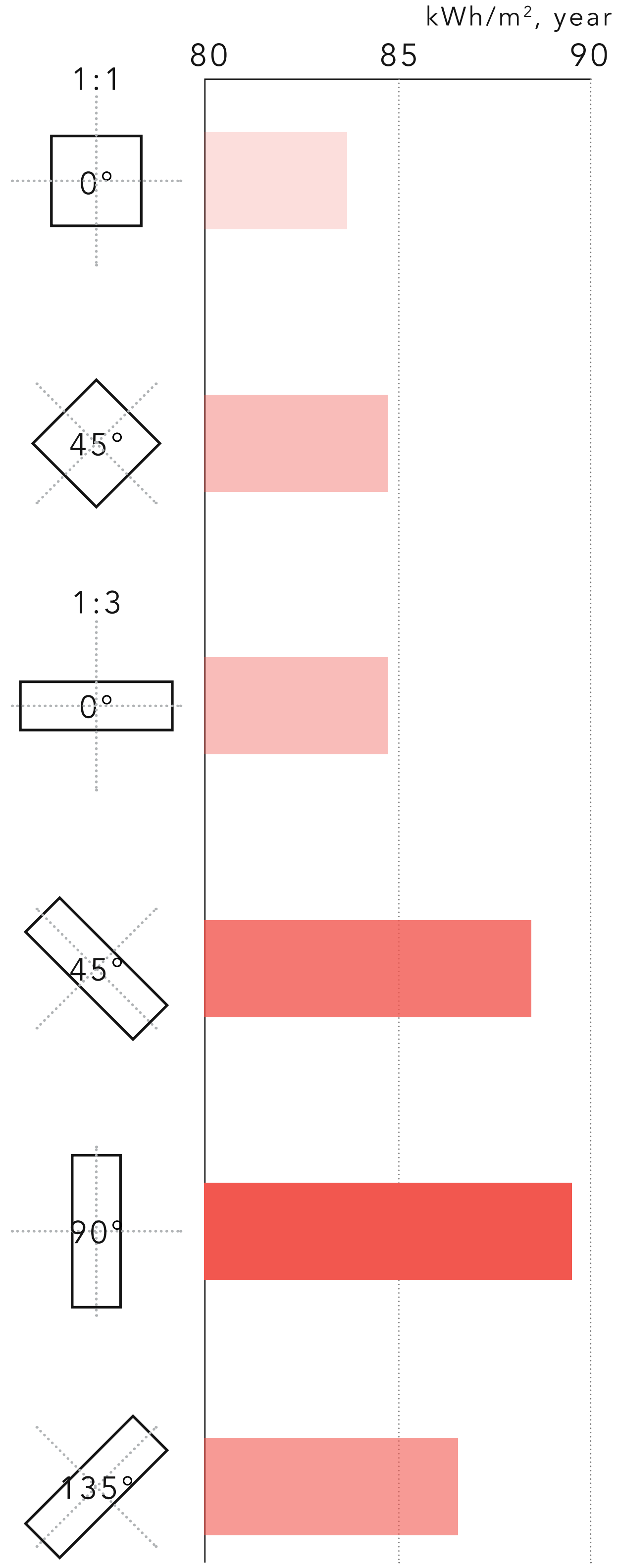


Figure 2.8: The energy impact of building orientation on different plan layouts (WWR = 50%) in a temperate climate
Source: Raji et al., 2017, p.18

2.4.2 HEIGHT

Tall buildings can have a significant impact upon the urban fabric of a city. Therefore, planning regulations which define the maximum height threshold for a region, the maximum allowable floor area ratio (FAR) or floor space index (FSI) and maximum building to land ratio (BCR), as well as distances from site borders, are usually the key factors which determine the maximum height of a building. Nevertheless, assuming that there would be no height constraint by the surrounding context and the local building regulations, which would be the maximum height that a building could reach today?

There are two major limitations when it comes to building height. The material strength of the structural elements is one of them, but it would still allow us to reach a building height of at least 1km *(Table 2.6)*.

The second limitation, is the economic viability of high-rise buildings which plays a major role in defining the building height. As the height of a building increases, so does the central core area due to increased loads and the need for additional vertical transportation. Central service cores contribute to the structural stiffness of the building, provide vertical transportation through elevators and staircases and incorporate toilets and M&E service ducts.

Keeping the service core area as efficient as possible while maximizing the net usable floor area is probably the most important design aspect when planning a high-rise building.

Today, vertical circulation technology can reach the limit of 60 floors without the need for transfer floors. Above this height, additional elevator shafts need to be added, which will increase the core area *(Gonçalves & Umakoshi, 2015)*. The service core area also determines the resistance of the building to the structural loads and implicitly affects the efficiency of the gross floor area (GFA) and net/usable floor area (NFA). According to *Yeang (1995; 2000)*, the floor area efficiency of a typical high-rise office building should not be less than 75% in order to make a building profitable. This ratio becomes very difficult to achieve for buildings >200m *(Sarkisian, 2016)*.

Taking the aforementioned aspects into consideration, this study uses the maximum height threshold of 200m as a target. This study will take into account the increase in core area relative to building height, and implicitly the increase in footprint area, in order to keep the floor efficiency at an economically profitable percentage of 80%.

Table 2.6: Energy Thresholds 2021
Source: Sarkisian, 2016

		Maximum Height
Compressive Strength Concrete MPa	34.5 MPa 69 MPa	1502 m 1502 m
Yield Strength Steel MPa	345 MPa 449 MPa	1502 m 1502 m

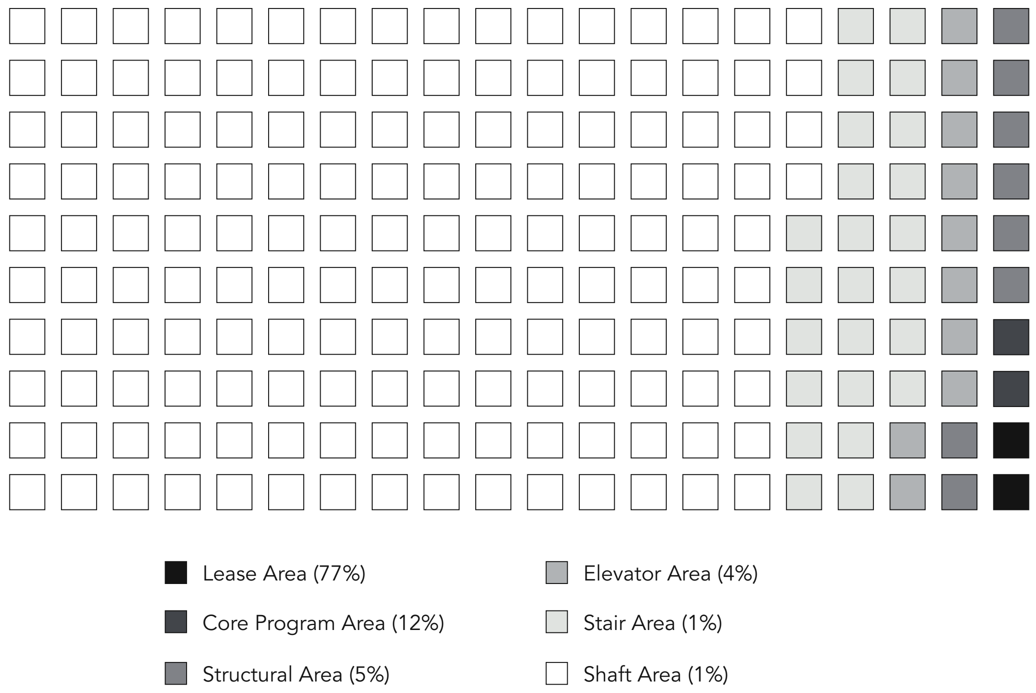


Figure 2.9: Average composition of GFA Resulting from Survey of Constructed Buildings (% of GFA)
Source: Sarkisian, 2016

2.4.3 SHAPE

The shape of the building has a significant role in the early design process, since it influences the plan layout, the degree of exposure to natural light and wind, the type of the structural system and the structural element sizes.

Previous studies have demonstrated that circular or elliptical building shapes are more energy efficient than rectilinear shapes in temperate climates, because of their compactness, hence the reduced exposure of the envelope area to sun and wind loads *(Raji et. al., 2017)*. *Figure 2.10* shows the total energy use with respect to the building shape, from the most efficient to the less efficient building shape for temperate climates. As stated above, the most compact shapes, mainly round shapes, are the ones requiring the least amount of energy.

Circular buildings also tend to be more aerodynamic, can minimize dynamic wind loads and induce natural ventilation more effectively. On the other hand, circular buildings are less efficient when it comes to layout planning compared to rectilinear buildings, where space can be used more efficiently.

In order to reduce the intensity of wind loads for rectilinear, hence more space efficient buildings, shape optimisation methods can be employed, such as: rounding, chamfering, or stepping back corners (ex. International Commerce Centre in Hong Kong by Kohn Pedersen Fox Associates), placing openings through the building in order to allow for air to flow through (ex. 432 Park Avenue tower in New York City by Rafael Viñoly Architects), incorporating vertical fins along the façade which help keep the wind flow attached to the building for longer, or varying the cross section shape along the height (ex. One World Trade Center in New York City by Skidmore, Owings & Merrill LLP).

Supertall or megatall buildings tend to change their floor layout shape along the height of the building or decrease in floor surface area towards the top. Tapered buildings, i.e., buildings which have a reduced area at the top of the tower, are more efficient in withstanding wind forces since the bending moment at the base of the tower is reduced (bending moment [M] = force [F] x distance [d]). Burj Khalifa in Dubai is a tapered tower, with a collection of rounded, stepped back tubes, which vary in height in order to disrupt vortex shedding along the height of the tower. However, this tapering, which allows for a much taller height limit, also reduces the area per floor, compared to shorter towers where the area per floor is maximized, as *Davis Langdon and Everest (1997)*, have demonstrated *(Table 2.7)*.

This study focuses on the energy performance of an office high-rise tower located in a temperate climate, with constant plan dimensions over the entire height of the building. Four shapes are being analysed, round, being identified as being the most energy efficient building shape, followed by square, rectangular and triangular, known as being more space efficient.

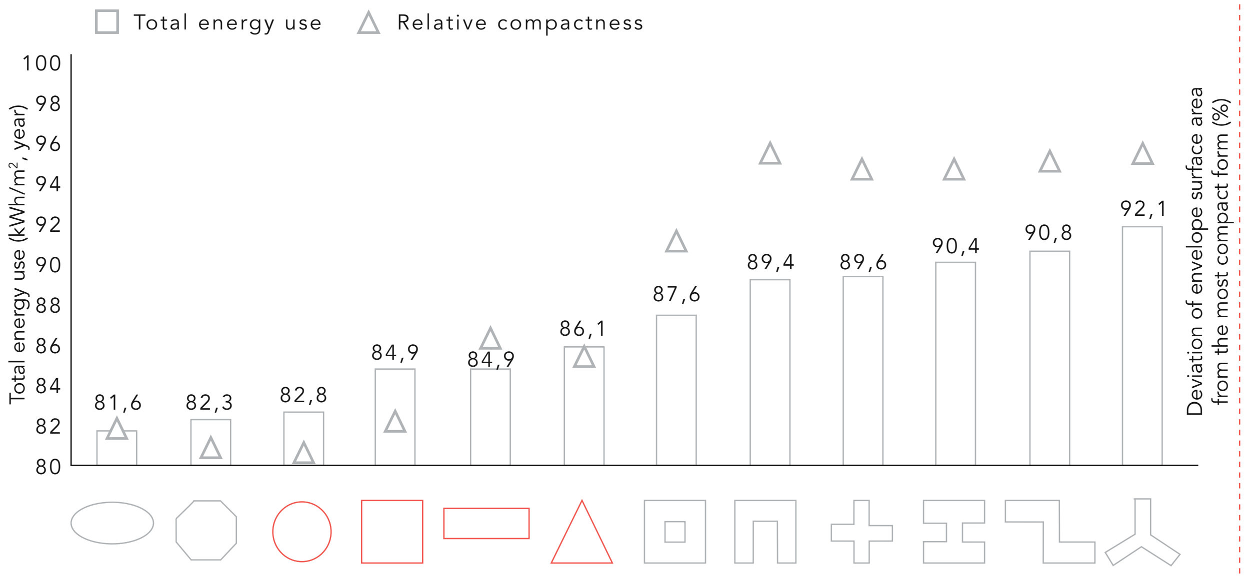


Figure 2.10: Building total energy use of 12 plan shapes (window-to-wall ratio (WWR) = 50%) in association with their compactness in Amsterdam
Source: Raji et al., 2017, p.15

Table 2.7: Building efficiency (net-to-gross floor area) of multi-story office developments
Source: Davis Langdon and Everest, 1997

Number of storeys	Efficiency %
2-4	83-86%
5-9	79-83%
10-19	72-80%
20-29	70-78%
30-39	69-75%
40+	68-73%

2.4.4 FACADE

Additionally to the building geometry, the facade plays a major role in the early design process of high-rise buildings. It defines the percentage of glazing relative to the wall area, i.e., the amount of daylight entering the space and thus affects the dependence on artificial lighting. It also determines the glazing surface that allows for natural ventilation, which implicily affects mechanical ventilation loads, cooling and heatin loads.

In a temperate climate, for an equal distribution of windows on all orientations (North, South, East, West), *Raji et al. (2017,p. 18)* claims the use of a window to wall ratio ranging between 20%-30% for narrow and deep plan design, respectively *Goia et al. (2013)* found the optimal value in the range of 35%–45% when exterior shading is used and the thermal performance of the external envelope is high.

However, there is not a single optimal window ratio that can be applied on all sides and floors of the building. In fact, each facade has a different exposure angle to the sun, in addition to the different exposure to the micro-climate conditions differing between the lower and upper floors. For example, on the South orientation, the higher the WWR (>30%), the higher also the cooling load, which is amplified even more at the top floors under the drop of air temperature. Thus, the WWR at the upper floors, where the exposure to the direct sun is higher, should be reduced *(Godoy-Shimizu et al., 2018)*.

Taking into consideration the different micro-climate conditions at ground floor and at the last floor of a high-rise building, it is more efficient to have a different WWR distribution for each façade orientation, varying with height, in respondse to the changing microclimate conditions, and the surrounding context height. As can be seen in *Table 2.8* and *Figure 2.11*, according to *Raji et al. (2017,p. 20)* the WWR can range from 10%-90% depending on window orientation.

Table 2.8: Recommended WWR value for different orientations and climates in which the deviation of total energy use is smaller than 1% from the optimal value in each orientation
Source: Raji et al., 2017, p.20

Climate Type/ Plan Aspect Ratio	Temperate		Sub-Tropical		Tropical	
	1 : 1	5 : 1	1 : 1	5 : 1	1 : 1	5 : 1
Recommended WWR value %	10-90	10-70	10-15	15-40	10-50	10-35
	35-60	No glazing	10-20	No glazing	10-20	No glazing
	65-75	25-35	10-70	10-40	10-80	10-55
	10-15	No glazing	10-20	No glazing	10-20	No glazing

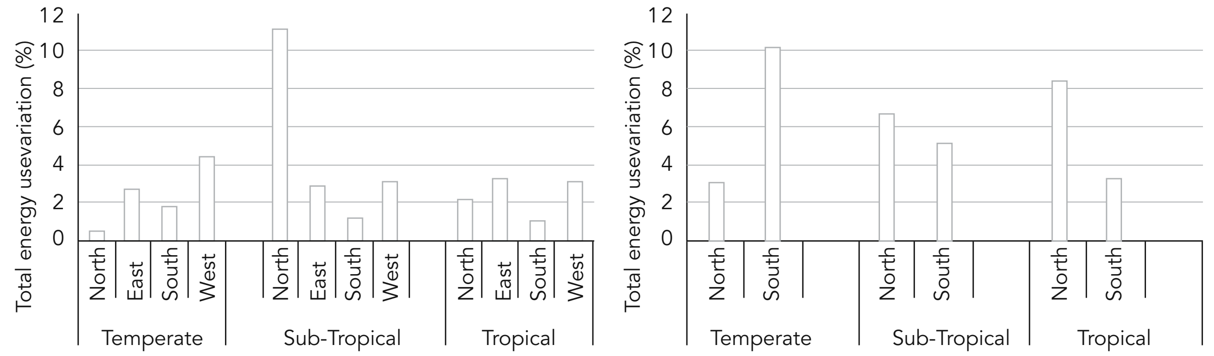
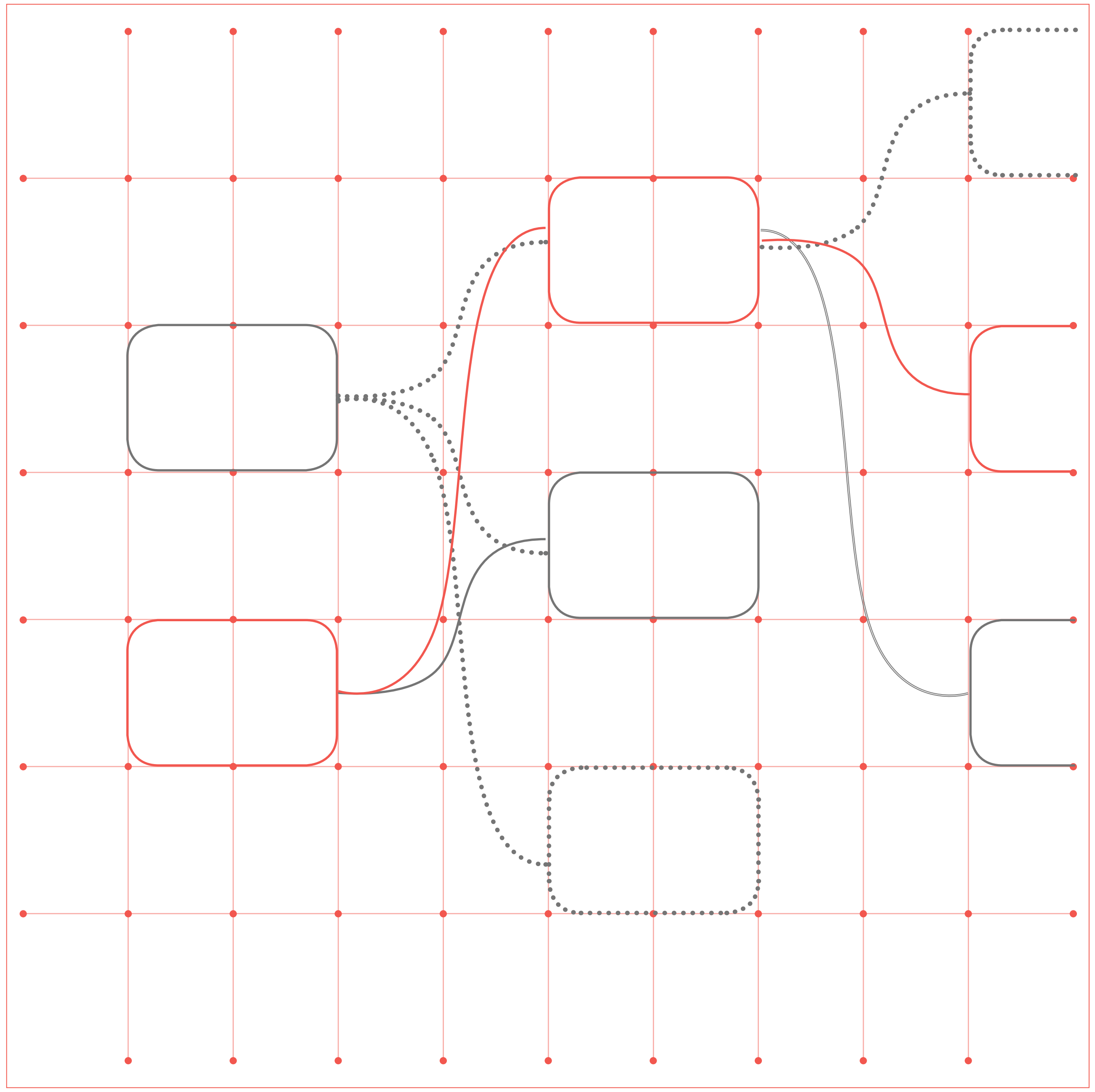


Figure 2.11: Sensitivity of different window orientations to a change in the WWR value (ranging from 10% to 90%) in terms of maximum variations in total energy use of a 40 storey office building with a deep plan and a narrow plan in temperate, sub-tropical and tropical climates
Source: Raji et al., 2017, p.20



3 Simulation Workflow

Simulation Workflow

3.1 INTRODUCTION

For the purpose of assessing the energy performance of a high-rise building relative to height, a fictitious office building is modelled on the ground of an old building in Sibiu, Romania. The current building is well known by the name "Tower Block" and dates back to 1960. The building is the first apartment block built in Sibiu, 9 storeys tall, and was originally designed as a hotel. Being located at the crossroad of two main boulevards, one that connects the south-east city exit to the historic centre, and the other being a direct main road to the south-west exit, the building could become an iconic urban landmark for the city. Unfortunately, the current building is in a degrading state, in desperate need for refurbishment, far from being an eye-catcher with landmark-quality.

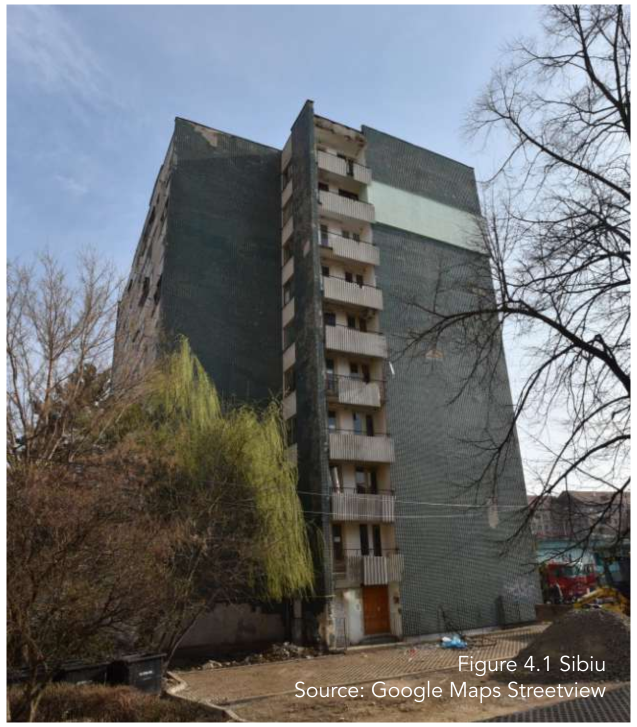


Figure 4.1 Sibiu
Source: Google Maps Streetview

Located in the same area are two other buildings, which are considered to be the "high-rises" of Sibiu, given that the urban fabric of the town is defined mainly by low-rise buildings. One of these buildings is Hotel Ramada, with an architectural height of 44,5m and the other one being Hotel Ibis, reaching 45m.

Considering the surrounding context and the favourable location for a high-rise building, this study is conducted on the plot of the current "Tower Block" of Sibiu. Given that the highest commercial building in Sibiu is 54m high (Sibiu Business Centre), a 50m office building is proposed for this plot. However, the microclimate does not change significantly from 0m to 50m, and in order to be able to define more precisely how the energy performance of a high-rise building is affected by height, another hypothetical high-rise building of ~200m will be simulated, although it is not fit for this specific context. This way, two building heights are being evaluated, building A, reaching ~50m, as suited for this context, and building B, reaching ~200m, in order to determine whether this height is even possible to be reached under the current primary energy threshold of 86 kWh/m^2.year.

The results will then contribute to the optimization of the geometry, orientation and façade for proposing an energy-saving optimal solution for a ~50m office high-rise building in the city centre of Sibiu and design guidelines are established for architects to assist them in the early design stage for other high-rise designs for temperate climates.

Figure 3.1 Perspective towards the building
Source: Google Maps Streetview

Figure 3.2 Perspective towards the building
Source: Google Maps Streetview

3.2 SIMULATION WORKFLOW

In order to evaluate the thermal comfort level and the energy performance of different high-rise design solutions, a parametric design workflow is set up in Grasshopper, while integrating the following software and plug-ins into the script: Ladybug and Honeybee Legacy Version 0.0.67 and Ladybug and Honeybee Energy Version 1.3.0, Radiance, Daysim, OpenStudio and Colibri.

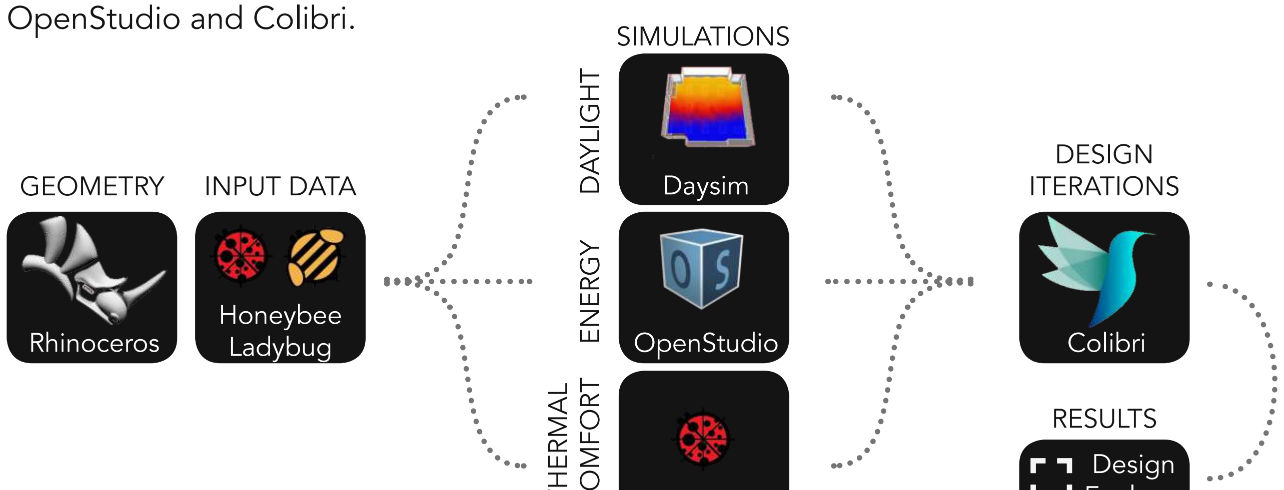


Figure 3.3 Simulation Workflow

CLIMATE DATA

In order to account for the impact of the surrounding context and changing microclimate conditions for the energy assessment of the two simulated high-rise buildings (~50m and ~200m), weather data representative of our city of study, Sibiu, is implemented into the script. The simulated building is located in an urban context, in the centre of Sibiu, Romania. The climate of Sibiu is a temperate climate, characterized by cold winters, and hot summers during the day, but cool during the night.

In order to account for the impact that the outdoor conditions have on the energy performance of the building, an epw (EnergyPlus Weather) climate file containing the yearly weather data of Sibiu was used for the simulation. The weather data provided by the epw file contains hourly information on the dry bulb temperature, relative humidity, solar radiation, wind speed and wind direction of the investigated location, all which have a significant impact on the energy performance.

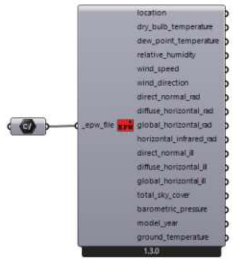


Figure 3.4 Workflow component for importing weather data

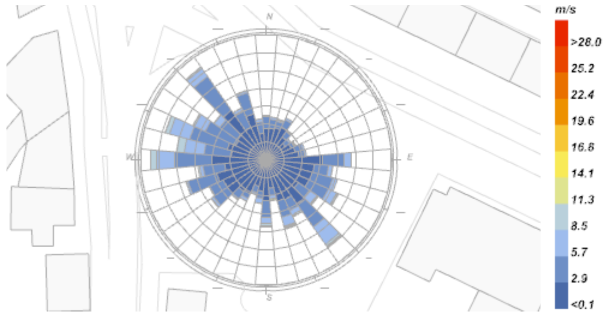


Figure 3.5 Annual wind directions and wind speeds for Sibiu, measured at 10m

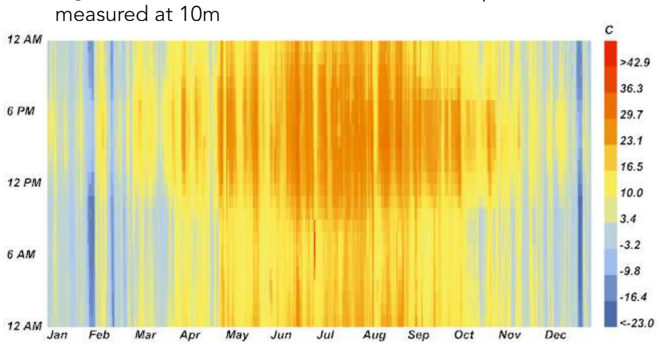


Figure 3.6 Hourly dry bulb temperature for Sibiu

3.2.1 GEOMETRY

SURROUNDING CONTEXT

The surrounding context was modelled by extracting the 2D outlines of the streets and buildings from CADmapper, based on which the buildings were modelled in Rhino, considering a floor-to-floor height of 3.50m. The surrounding buildings are predominantly low, with only a few reaching 40-45m. In order to evaluate the degree of impact the surrounding can have on the energy performance of a high-rise building located in an urban context, we consider also a scenario in which the existing buildings will increase in height over the next years, transforming into a mid-rise surrounding context. In this case, two context types are being evaluated: type 0, representing the current low-rise situation and type 1, corresponding to a hypothetical mid-rise scenario.

BUILDING HEIGHT

The energy performance of two building types is being analysed, a ~50m high one and a ~200m one. The energy simulation is carried out for each building individually, at two levels, the 2nd level (4,2m) and at the second but last level. Thus, we are able to determine by how much the energy demand increases with height and whether a ~200m building height can be reached under the maximum required primary energy threshold of 86 kWh/m^2.year. The performance of the two buildings is being analysed under the influence of the two different context scenarios, the current low-rise surrounding and a futuristic mid-rise surrounding scenario *(Figure 3.7, 3.8, 3.9, 3.10)*.

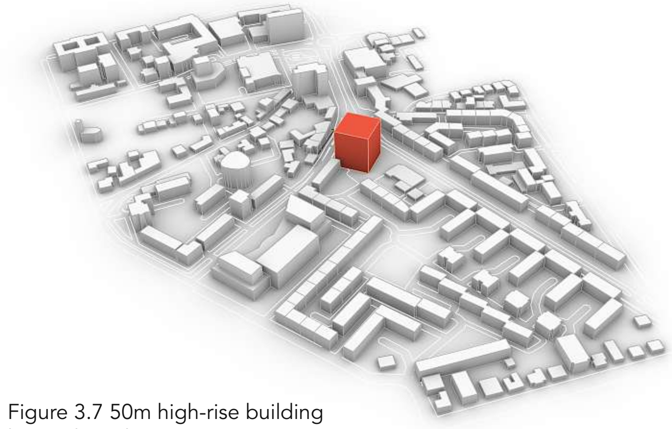


Figure 3.7 50m high-rise building located in a low-rise context

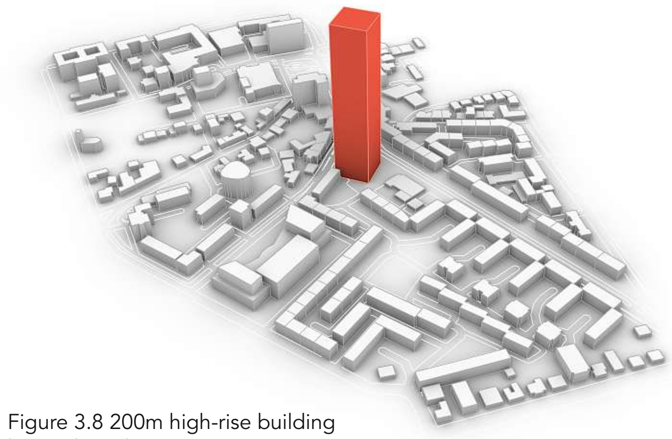


Figure 3.8 200m high-rise building located in a low-rise context

Figure 3.9 50m high-rise building located in a mid-rise context

Figure 3.10 200m high-rise building located in a mid-rise context

CORE TO GFA RATIO

As far as morphological variables are concerned, four building shapes are being analysed, round, being identified by *Raji et al. (2017, p.11)* as being the most energy efficient building shape, followed by square, rectangular and triangular, known as being more space efficient. The simulated building is an office building, following a typical open plan layout with a core to GFA relationship of 20%-80%.

As has been identified through the literature review, this 20%-80% ratio can be maintained only if the building footprint area increases proportionally with the height increment, due to increased loads, i.e., bigger structural elements in size, and the need for additional vertical transportation with height. Therefore, in order to evaluate the energy performance of a ~200m high-rise building compared to a ~50m building, it is essential to determine how much the footprint area of a high-rise building increases with height. For this study, 60 existing high-rises ranging from 50-632m were assessed in terms of height, footprint area and core area. The relationship between the building height and the footprint area can be visualized for 15 round, 15 square, 15 rectangular and 15 triangular buildings in *Figures 3.11-3.14*. Data on the height, footprint GFA and core area of the selected high-rises can be found in *Figures 7.1-7.4* of the *Appendix*.

Using the analytical expression of the regression curves, a function was obtained for each building shape, to calculate "y", the GFA in m², based on "x", the building height in meters. For a different set of data, one can obtain slightly different functions for the analytical expression of the regression curves, but for reaching the purpose of this study, these differences are insignificant.

The 15 data entries indicate an average GFA of 600m² for a ~50m building and 1800m² for a ~200m high one, i.e, a 400m² increase with every 100m. For the 15 data entries for each building shape, the relationship between core area and footprint area was evaluated as well. As several studies also indicate, the core area of the evaluated high-rise buildings ranges between 15-33%, with most buildings having a core area of 15-20%.

Shape	50m	200m	Increase
Round	505m²	1395m²	+890m² x 2.8 increase
1:1	690m²	1685m²	+995m² x 2.4 increase
1:2	700m²	2150m²	+1450m² x 3.1 increase
Triangle	475m²	1780m²	+1305m² x 3.8 increase
Average input values	600m²	1800m²	+1200m² x 3 increase

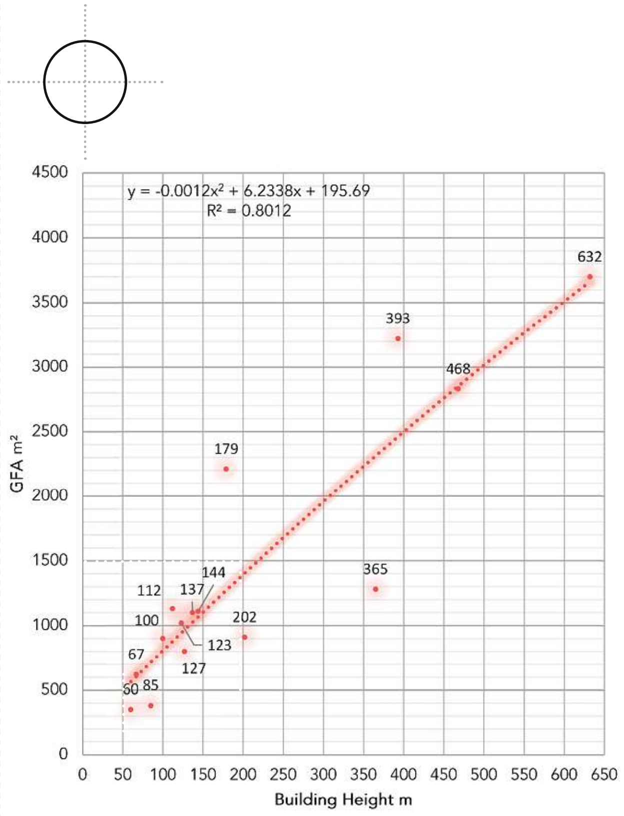


Figure 3.11: Ground Floor Area Increase with Height for Round High-Rises

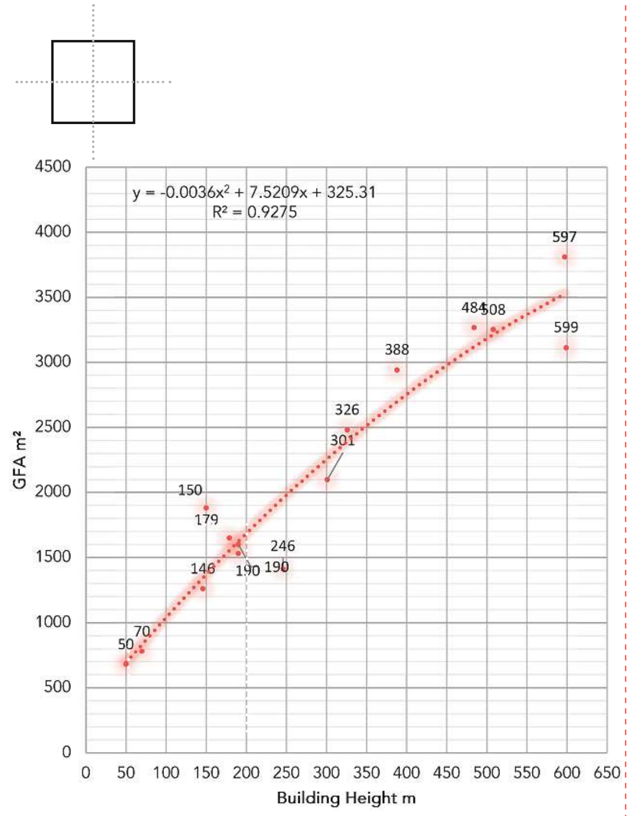


Figure 3.12: Ground Floor Area Increase with Height for Square High-Rises

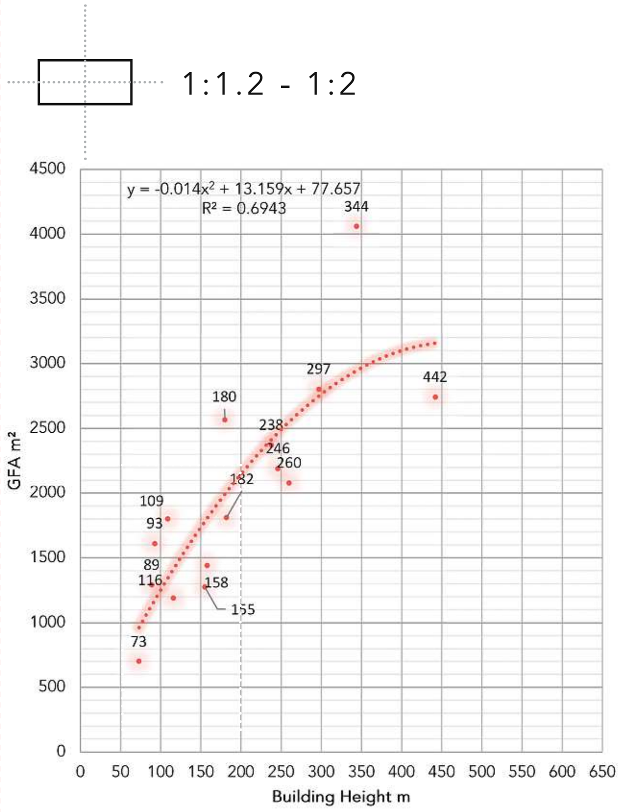


Figure 3.13: Ground Floor Area Increase with Height for Rectangular High-Rises

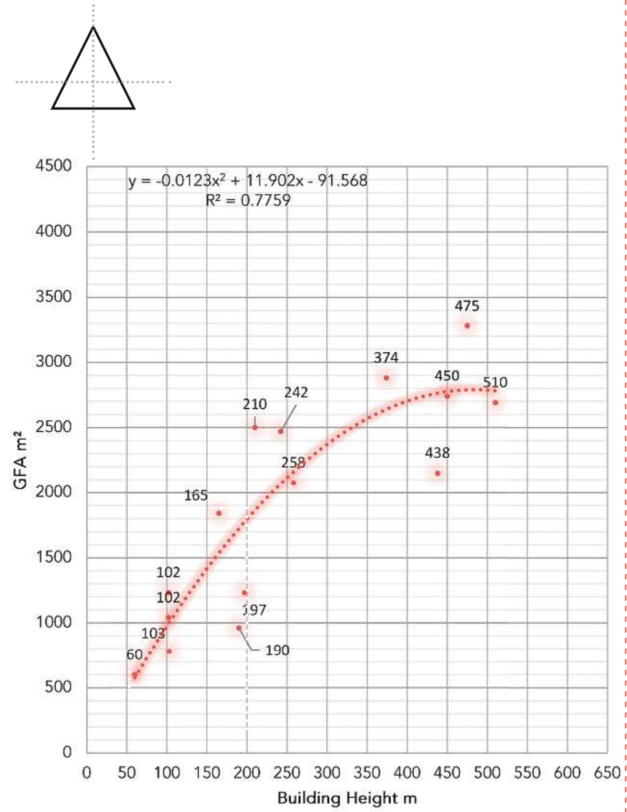


Figure 3.14: Ground Floor Area Increase with Height for Triangular High-Rises

• Total GFA ······ Poly. (Total GFA)

PLAN LAYOUT DIMENSIONS

Considering the aforementioned observations, this study will assess the performance of an office high-rise building with a core to GFA relationship of 20%-80%. building A (~50m) will have a footprint area of 600m² for all evaluated building shapes and building B (~200m) will have a footprint area of 1800m² over the entire height.

To assess the impact of compactness on energy performance, the shape factor was calculated for the four evaluated plan layout shapes for building A and B, based on the thermal envelope area and volume as follows *(Table 3.1 and Table 3.2)*:

$$\text{Shape Factor } [1/m^2] = \frac{\text{Thermal Envelope Area } [m^2]}{\text{Building Volume } [m^3]} \quad [3.1]$$

ORIENTATION

This study also analyzes the impact of the orientation on the energy performance and indoor comfort conditions. Therefore, we consider different rotation angles for each plan layout shape, as represented below in *Figure 3.15*.

Taking into account the impact of the surrounding context and the change in microclimate conditions with height, it could be that a different rotation angle is suited at the top than at the bottom of the building. Therefore, simulations are performed at the second level (4,2m) and at the second but last level (42m, respectively 193,2m).

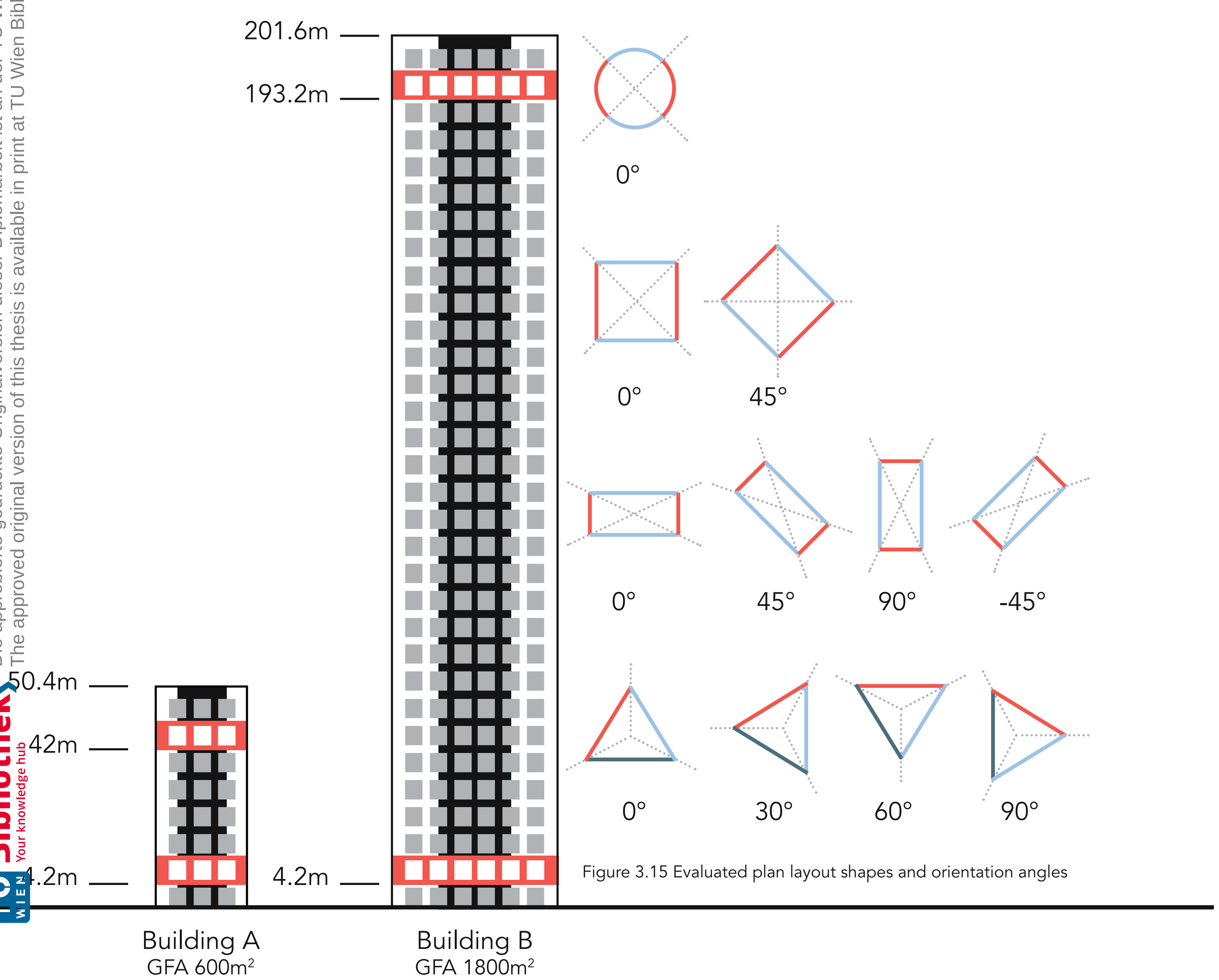


Figure 3.15 Evaluated plan layout shapes and orientation angles

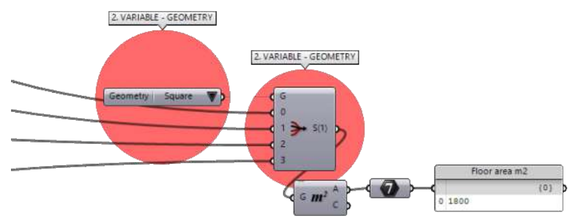


Figure 3.16: Workflow components for evauating different building shapes

Table 3.1: Shape factors of the different building geometries for building A (50.4m)

	Shape	Height	Footprint Area	Thermal Envelope Area	Volume	Shape Factor
		m	m²	m²	m³	
Building A	Round	50.4	600	5605	30240	0.19
	Square	50.4	600	6139	30253	0.20
	Rectangular	50.4	600	6438	30238	0.21
	Triangular	50.4	600	6833	30190	0.23

Table 3.2: Shape factors of the different building geometries for building B (201.6m)

	Shape	Height	Footprint Area	Thermal Envelope Area	Volume	Shape Factor
		m	m²	m²	m³	
Building B	Round	201.6	1800	21220	362880	0.06
	Square	201.6	1800	37816	362942	0.10
	Rectangular	201.6	1800	39888	362880	0.11
	Triangular	201.6	1800	42591	362880	0.12

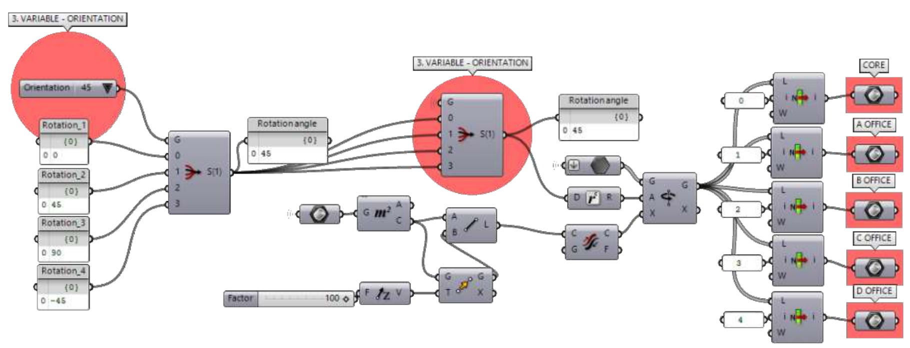


Table 3.17: Workflow components for evauating different rotation angles

3.2.2 INPUT DATA

BUILDING PROGRAM

In order to take into account internal equipment loads for the energy simulation, a "MediumOffice" building program is assigned to all rooms and internal loads and schedules are specified for the core and office areas as follows.

HOT WATER: The hot water usage per person is determined considering an amount of 3 L/day per person for dishwashing and 13 L/day per person for handwashing. This adds up to 0.67 L/h per person, considering an "OfficeServiceHotWater" schedule for hot water usage over the course of the year. The hourly service water consumption is represented in the *Appendix, Figure 7.3*.

EQUIPMENT: Assuming that most of the office work is carried out on computers, an equipment load of 5W/m² is considered, whereas a fraction of 0.3 of that load is given off as long wave radiant heat. In addition, a "GenericOfficeEquipment" schedule is assigned to the equipment object. The hourly equipment usage is represented in the *Appendix, Figure 7.2*.

LIGHTING: A lighting load of 3W/m² is considered for the core and office spaces, whereas half of that is given off as long wave radiant heat in the room. In addition, a "GenericOfficeLighting" schedule is assigned to the lighting object. However, the lighting schedule will be overwritten based on the amount of solar gains with respect to the change in shape, orientation and window to wall ratio for each design variation.

INFILTRATION RATE: As specified by the Methodology for calculating the energy performance of buildings in Romania *(Metodologie de calcul al performantei energetice a ..., 2021, p. 68)*, the infiltration rate of an nZEB building needs to be q<1,0m³/h.m² at 50Pa, which equals to q<0,0003m³/s.m². An infiltration rate of 0,0001m³/s.m² is considered for this study, corresponding to an air tight building.

OCCUPANCY: According to *EN 15251:2006 (pg.34)*, 1 person/15m² can be considered for a landscaped office layout. This means, a numerical value of 0,07 people per m² will be used as degree of occupancy. In addition, a "Generic Office Occupancy" schedule is assigned to the occupancy object. The hourly degree of occupancy is represented in the *Appendix, Figure 7.1*.

VENTILATION: According to *EN 15251:2006 (pg.34)*, a ventilation rate of q=0,5 l/s.m², which is equivalent to 0,0005 m³/s.m², is the minimum requirement for ventilation for a landscaped office plan with an occupancy of 1 person/15m².

ADJACENCIES

In order to account for heat flows between adjacent rooms, interior separation walls need to be identified, as well as the surfaces representing the exterior walls, floors and ceiling. The component "HB Solve Adjacencies" is used to identify these surfaces and categorize them as external/internal walls and floor/ceiling surfaces. By doing so, the geometry is divided into two thermal zones, the core area and the office area. The open office area is divided into four office zones, respectively three office zones for the triangular plan layout. The partition walls are defined as "air walls", so that there is a heat exchange between the four compartments. This subdivision is needed because the program cannot identify the different surfaces for a donut-shaped floor plan, i.e., core in the middle and an open office space around *(Figure 3.26)*.

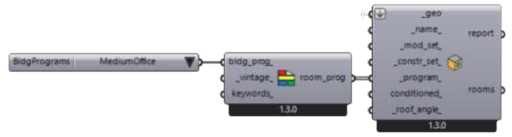


Figure 3.18: Workflow components for adding the building program

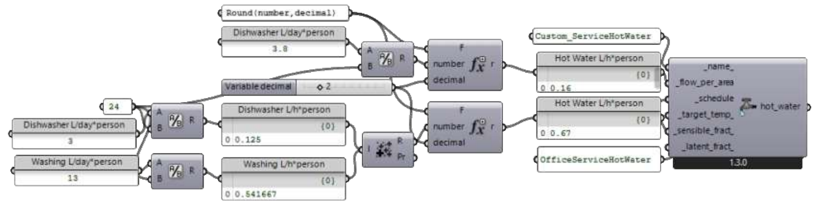


Figure 3.19: Workflow components for service hot water consumption

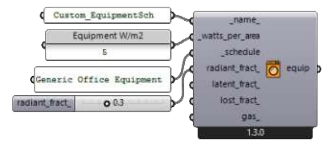


Figure 3.20: Workflow components for equipment loads

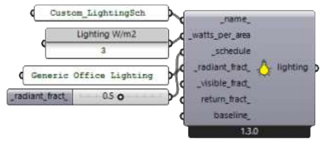


Figure 3.21: Workflow components for lighting loads

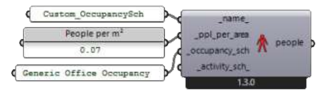


Figure 3.22: Workflow components for the occupancy schedule

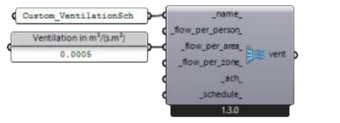


Figure 3.23: Workflow components for ventilation rate

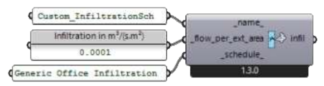


Figure 3.24: Workflow components for infiltration rate

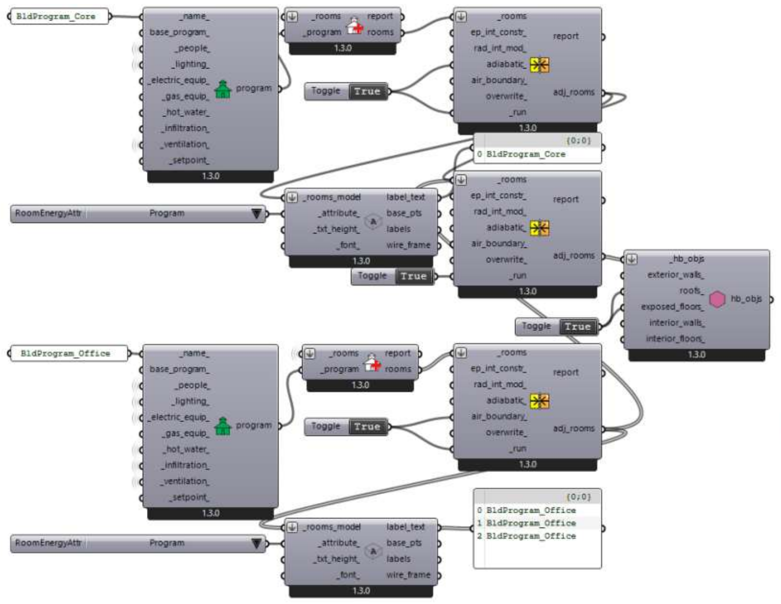


Figure 3.25: Workflow components for solving adjacencies

Source: Workflow components from Grasshopper for Rhino 6.0

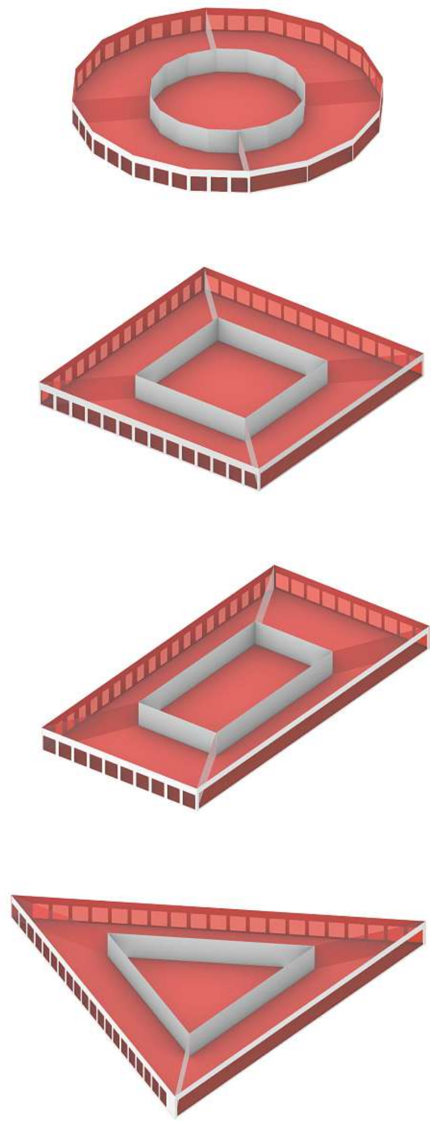


Figure 3.26: Simplified floor plan for workflow

WINDOW TO WALL RATIO

Three different window-to-wall ratios are being analysed for each side of the facade, a glazing percentage of 35%, 50% and 65%. The windows are assigned to the exterior walls using the "HB Apertures by Ratio" component. In order to streamline the simulation time, a horizontal separation of 3 meters between the windows is set. The lower this value is, the longer the simulation time. The width of the windows varies for each geometry depending on the length of the parent exterior wall surface and the horizontal separation distance. The windows are 2.6m high, with a sill height of 0.3m.

GLAZING

Triple glazing with aluminium window frames is considered as an efficient design solution for this study. The selected U-value of 0.6 W/m²K is equivalent to the frame+glass assembly. A solar heat gain coefficient of 0.5 and a visual light transmittance of 0.75 is considered for this study. The presented properties were assigned to the "HB Window Material" component.

SHADING

In order to prevent overheating and glare issues, interior blinds are assigned to the windows. The shading system is operated automatically and blinds go down when the incidental solar load on the glazing surface exceeds 200 W/m².

MATERIALS

As a next step, the material properties are defined for each surface individually using the "HB Opaque Construction" component. The layer composition of each surface is summarized in *Table 3.4*.

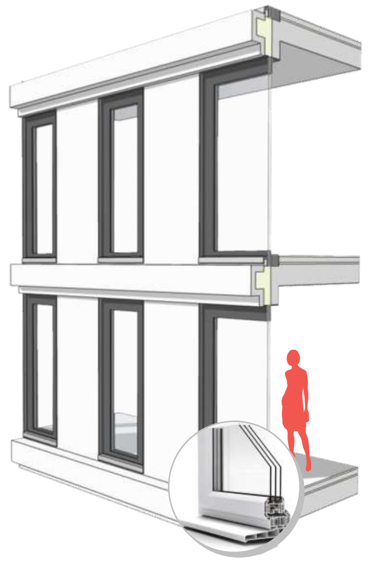


Figure 3.27: WWR type 1 - 35%

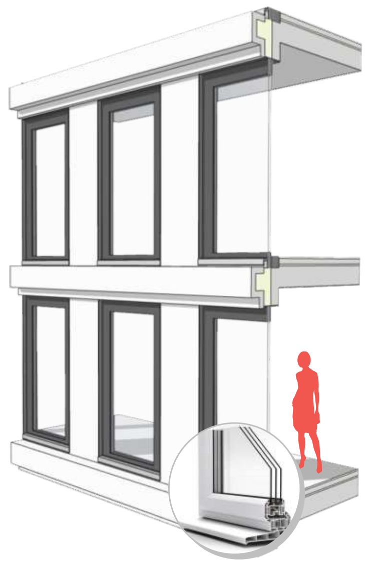


Figure 3.28: WWR type 2 - 50%

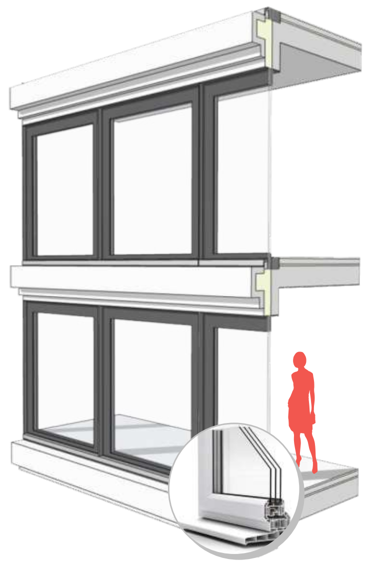


Figure 3.29: WWR type 3 - 65%

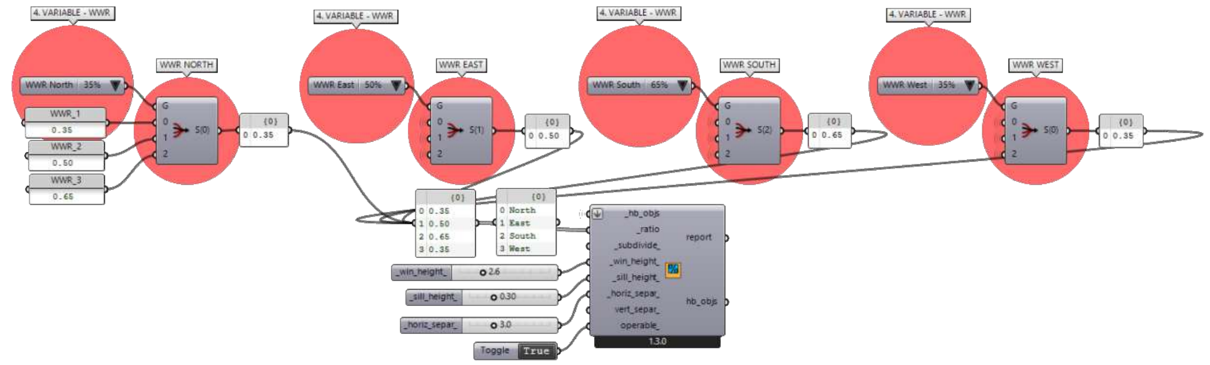


Figure 3.30: Glazing and shadin properties
Source: Workflow components from Grasshopper for Rhino 6.0

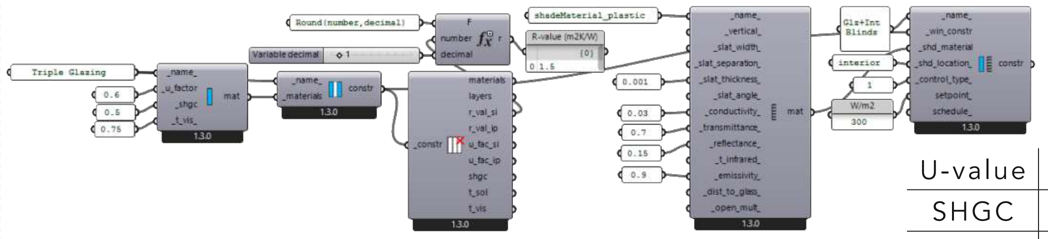


Figure 3.31 Glazing and shadin properties
Source: Workflow components from Grasshopper for Rhino 6.0

U-value	0.6
SHGC	0.5
VLT	0.75

Table 3.3: Glazing properties

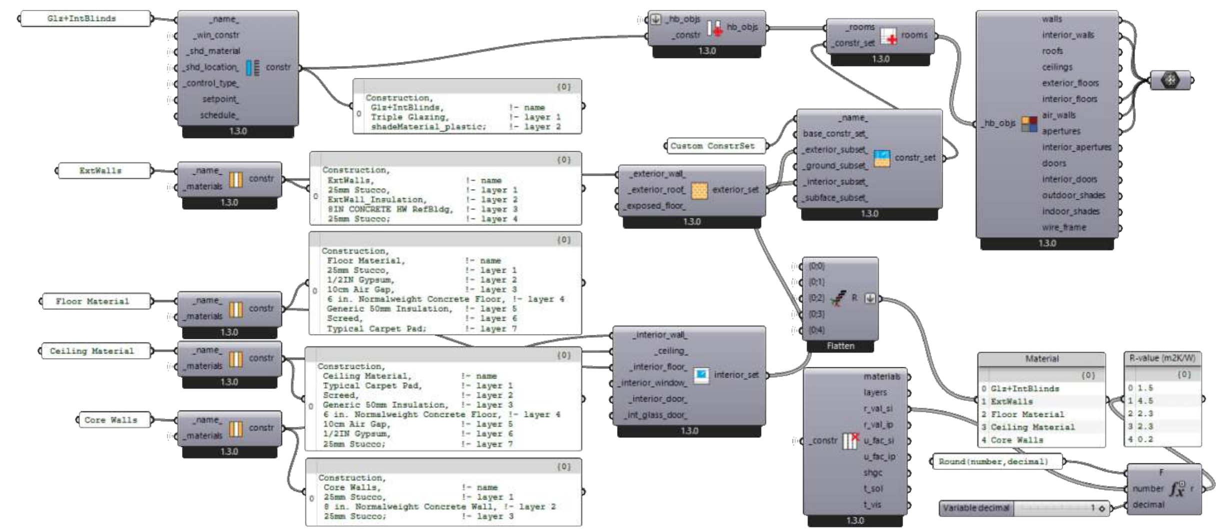


Figure 3.32: Building layers and thermal properties for exterior walls, core walls, floor and ceiling

Table 3.4: Thermal Resistance Values for Exterior Walls, Core Walls, Floor and Ceiling

	Exterior Walls	Core Walls	Floor/Ceiling
	25mm Stucco	25mm Stucco	Typical Carpet Pad
	15cm Rockwool Insulation	20cm Concrete Wall	30mm Screed
	20cm Concrete Wall	25mm Stucco	50mm Insulation
	25mm Stucco		15cm Concrete Slab
			10cm Air Gap
			12mm Gypsum Board
			25mm Stucco
Total R-value	4.5 m²K/W	0.2 m²K/W	2.8 m²K/W

NATURAL VENTILATION

Natural ventilation is simulated through the use of the component "HB Window Opening". Assuming that natural ventilation is induced by tiling the windows, a fraction of 0.3 of the window area is considered as being operable. Natural ventilation is conditioned by interior and exterior factors, which need to be met in order to allow for windows to open. First, the outdoor temperature has to be within a range of 18°C and 25°C, with a maximum allowable wind speed of 7.0 m/s. Secondly, the indoor temperature needs to be at least 22°C and at most 25°C in order to allow for natural ventilation. This means natural ventilation is not user controlled but conditional and will be enabled only if the aforementioned indoor and outdoor conditions are met. If the temperature or the wind speed do not allow for natural ventilation, mechanical ventilation is activated *(Figure 3.33)*.

MECHANICAL VENTILATION, HEATING and COOLING

Mechanical ventilation is enabled whenever the indoor, outdoor temperatures and wind speed do not allow for natural ventilation. The alternation between mechanical and natural ventilation is happening only for the office spaces, which are provided with openings at the façade. The core area is mechanically ventilated throughout the entire year. Mechanical ventilation is supplied through the use of a DOASystem, a dedicated outdoor air system, connected to a ground water source heat pump. DOASystems separate the minimum ventilation supply from the heating and cooling demand, which can save fan energy. By using a DOASystem in combination with a ground source water heat pump, it is possible to supply the DOAS coils with hot/cold water, depending on the heating/cooling demand, instead of blowing hot/cold air. The heating and cooling efficiency is defined by COP=3.6, respectively EER=12, which are typical values for ground source water source heat pumps.

In addition, we consider using an enthalpy wheel for energy recovery. The enthalpy wheel recovers both sensible and latent heat. For this study, we consider a sensible heat recovery effectiveness of 0.8 and a latent heat recovery effectiveness of 0.7 (values can range between 0 and 1).

The amount of mechanical ventilation is defined by the required minimum ventilation rates in relation to the occupancy (demand-controlled ventilation). The heating and cooling setpoints are defined in accordance with *EN 15251:2006 (pg.26)*. The latter suggests a minimum required operative temperature for heating in winter, considering clo=1,0 (clothing level), of 21°C and a minimum required operative temperature for cooling in summer, considering clo=0,5 (clothing level), of 25,5°C, if PPD<6% (Predicted Percentage of Dissatisfaction) is to be achieved.

For this study, a heating setpoint of 21°C is considered. As far as cooling is concerned, preliminary analysis showed a low thermal comfort level when a setpoint of 25,5°C for cooling was used, leading to a high percentage of dissatisfaction due to overheating issues. Therefore, a lower cooling setpoint of 24°C was selected.

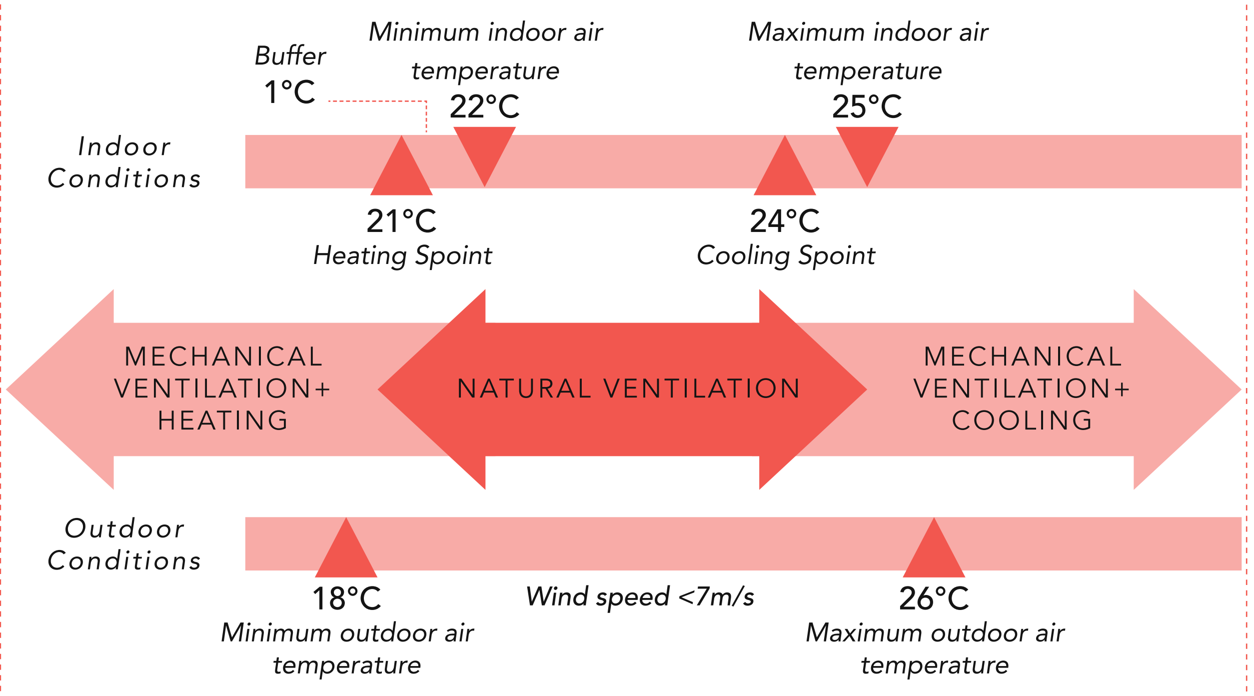


Figure 3.33: Temperature set point conditions for natural ventilation, mechanical ventilation, heating and cooling

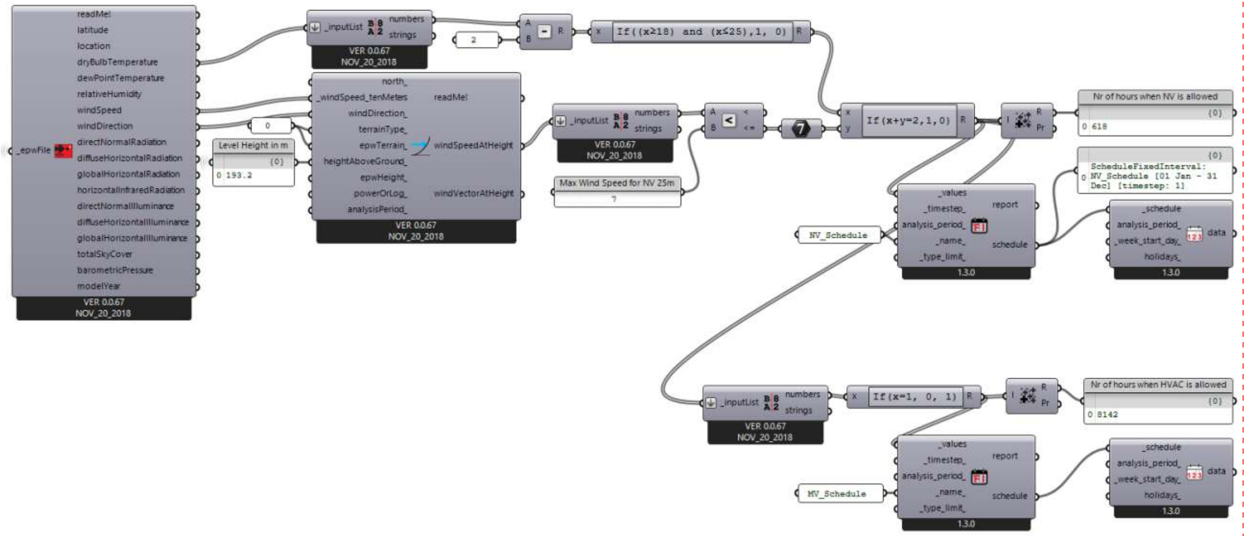


Figure 3.34: Natural ventilation and mechanical ventilation schedules

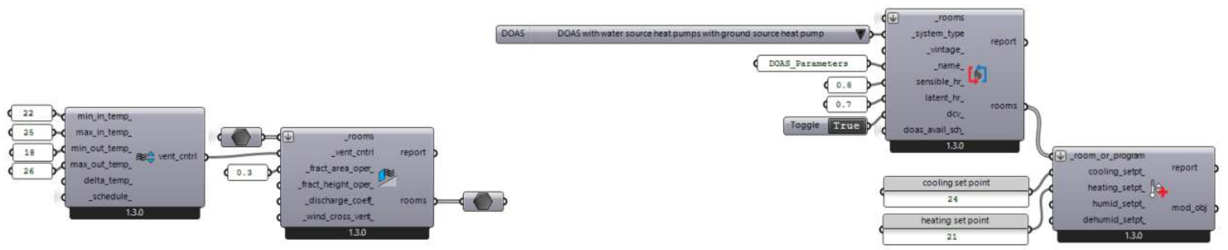


Figure 3.35: Mechnical ventilation, heating and cooling schedules

Source: Workflow components from Grasshopper for Rhino 6.0

Before performing the iterative optimization process, it is essential to summarize the information which will serve as input for the simulation workflow. The following section summarizes the energy and thermal comfort benchmarks which are derived from the literature review. Apart from the constant input values, this section provides an overview of the variables for the iterative design process.

INPUT DATA

CLIMATIC DATA

Temperate Climate (.epw file for Sibiu, Romania)

ENERGY BENCHMARKS

Total primary energy 86 kWh/m²,year
Total CO_2 emissions 9.9 kg/m²,year
Min. renewable energy 30%

THERMAL COMFORT BENCHMARKS

Predicted Percentage of Dissatisfaction PPD < 10%
Predicted Mean Vote (PMV)
- 0.5 < PMV < +0.5

CONSTNAT HIGH-RISE CHARACTERISTICS

Function: Office
Floor to Floor Height: 4.2m

USER REQUIREMENTS

Occupancy:
Working Day Schedule (Mo-Fr)
8:00-17:00

Hot Water Load: 0.67 L/h per person
Equipment Load: 5W/m²
Lighting: 5W/m² if <500 lux
Infiltration Rate: 0,0001m³/s.m²
Occupancy: 1 person/15m²
Ventilation Rate:0,0005 m³/s.m²

VENTILATION & HEATING CONSTANTS

Natural Ventilation:
Windows opening: 0.3 fraction of total glazing
Wind speed < 7m/s
Min. indoor temp.: 22°C
Max. indoor temp.: 26°C
Min. outdoor temp.: 18°C
Max. outdoor temp.: 26°C

Mechanical Ventilation, Heating and Cooling:
DOASystem in comb. with a ground source heat pump
Cooling EER = 12
Heating COP = 3.6
Heat Recovery: Sensible Heat 0.8, Latent Heat 0.7
Cooling Set Point = 24°C
Heating Set Point = 21°C

Water Heating:
COP = 3.6

FACADE CONSTANTS

R-values Envelope	(m²K/W)
Exterior Walls	4.5
Core Walls	0.2
Floor/ Ceiling	2.8

Shading System:
Automatically controlled interior roller blinds (white fabric) when solar irradiation >200W/m²

FACADE GENERATION

Energy Generating Systems:
Ground source heat pump
Roof covered at 90% with PV of efficiency 20%

VARIABLES

SURROUNDING CONTEXT
type 1: Low-rise surrounding
type 2: Mid-Rise surrounding

HEIGHT
type 1: Building A (~50m):
simulation at 4.2m and 42m
type 2: Building B (~200m):
simulation at 4.2m and 193.2m

SHAPE
Type 1: Round
Type 2: Square
Type 3: Rectange (1:2)
Type 4: Triangle

ORIENTATION ANGLE
Cirular: 0°
Square: 0°, 45°
Rectangular: 0°, 45°, 90°, -45°
Triangular: 0°, 30°, 60°, 90°

WINDOW TO WALL RATIO
Type 1: 35%
Type 2: 50%
Type 3: 65%

TOTAL NUMER OF ITERATIONS

Building A (50m):
3564 Iterations
**only 648 iterations are be carried out for a square building shape*

Building B (200m):
3564 Iterations
**all iterations are carried out for all design variations*

3.2.3 OUTPUT DATA

In order to define the most optimal design parameter combinations for the studied climatic and surrounding context conditions, the energy performance and thermal comfort conditions are evaluated for all the possible design solutions.

DAYLIGHT SIMULATION
for LIGHTING LOADS

A daylight simulation is performed for each design version in order to determine the incoming solar gains and implicitly the resulting lighting loads. The lighting threshold for the daylight autonomy was set to 500 lux, in accordance with *EN 15251:2006* for the minimum requirement for an open plan office layout. If the 500lux are not met during occupancy, the light will be turned on. The shadow generated by the surrounding context is also accounted for. In order to reduce the simulation time, the grid cell size of the generated daylight autonomy mesh is increased to 3.

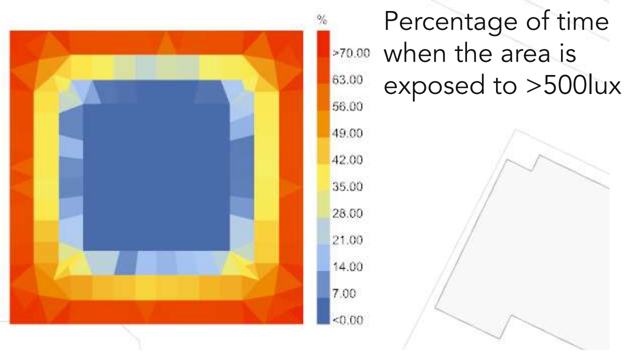


Table 2.4: Spatial Daylight Autonomy for a rectangular floorplan

ENERGY SIMULATION
for PRIMARY ENERGY USE

In order to quantify the energy performance of each design version, different energy loads are calculated using the "Open-Studio" Component. Energy loads for heating, cooling, hot water, lighting, equipment, fans and pumps are calculated over a yearly period. The end use is expressed in kWh/m^2.year and represents the sum of heating/cooling, fuel and electricity used, divided by the total floor area. For the calculation of the primary energy use, heating and hot water loads are divided by 3,6 (COP), respectively cooling loads by 12 (EER). To account for energy losses through transmission and transfer, the primary energy demand is calculated with a primary energy factor specified by the Methodology for calculating the energy performance of buildings in Romania *(Metodologie de calcul al performantei energetice a ..., 2021)*, namely, a primary energy conversion factor of 1,53 is considered for heating and hot water consumption, 1,00 for cooling and 2,62 for lighting, electrical equipment, fans and pumps.

RENEWABLE ENERGY

Assuming that 90% of the roof area is used for energy production with PV panels with an efficiency of 20%, the amount of renewable energy is calculated using the "Ladybug_Photovoltaics Surface" Component. A primary energy conversion factor of 2,62 is considered for calculating the primary energy produced by PV panels. The resulting energy in kWh/m^2.year will then be subtracted from the primary energy need, calculated as mentioned previously. The result represents the final total primary energy demand.

In order to determine whether the minimum requirement of 30% renewable energy can be met, the percentage of renewable energy produced by the PV area was calculated based on the following formula:

$$\text{Percentage of Renewable Energy [\%]} = \frac{\text{Produced Primary Energy [kWh/m}^2\text{, year]}}{\text{Primary Energy Need + Produced Primary Energy [kWh/m}^2\text{, year]}} \cdot 100 \qquad [2]$$

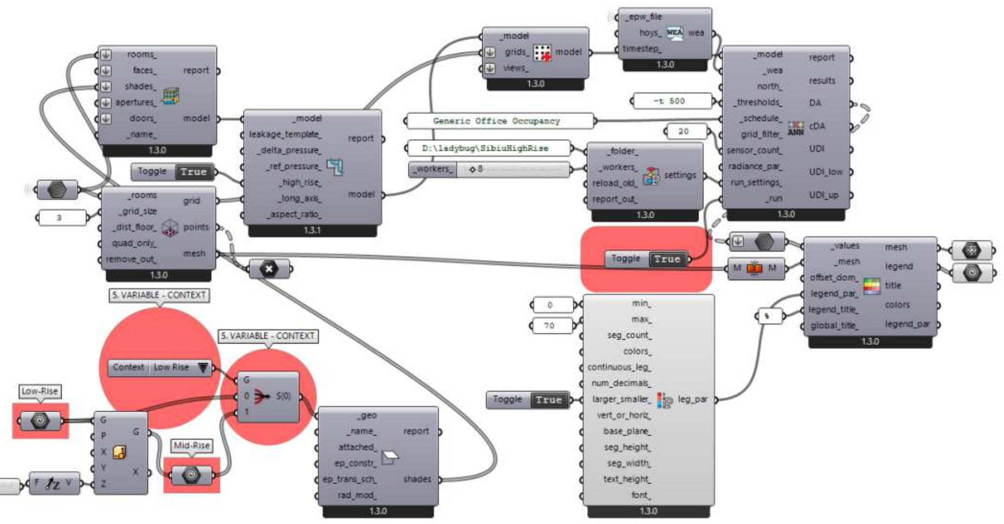


Figure 3.36: Workflow components for running the daylight simulation

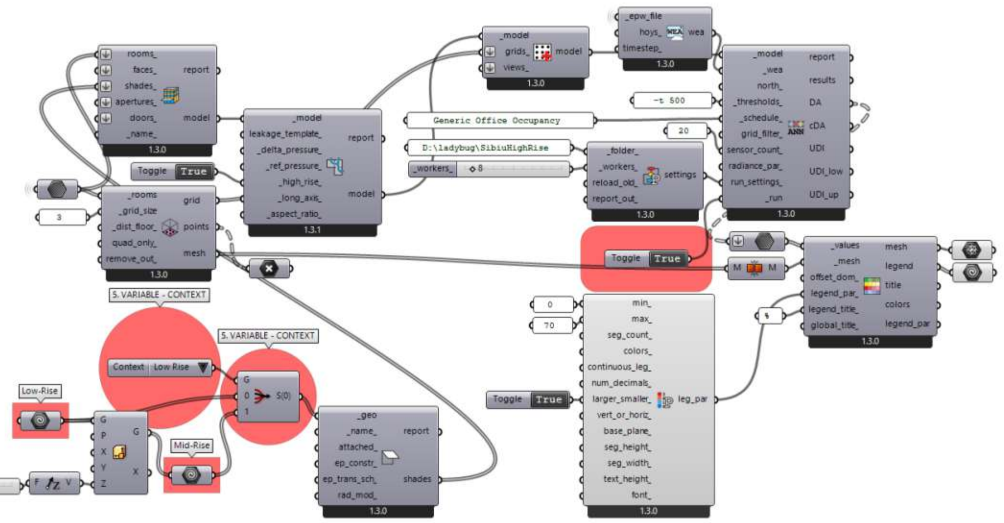


Figure 3.37: Workflow components for running the energy simulation

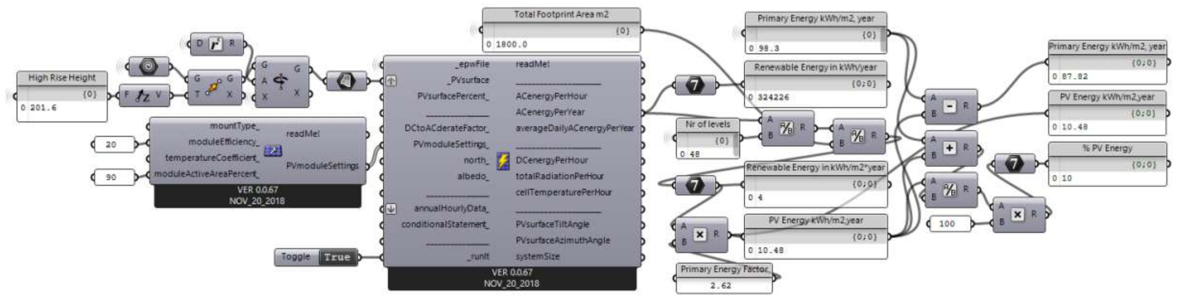


Figure 3.38: Workflow components for calculating the primary energy produced by PV panels

THERMAL COMFORT SIMULATION for % OF FEELING COMFORTABLE

Data concerning the thermal comfort conditions are extracted for each design version. The indoor comfort level is evaluated in accordance to the European standard *EN 15251:2006*, where a comfort level of 90% is expected for buildings of category II, i.e., new buildings and renovations.

The percentage of time feeling comfortable is calculated using the component "LB PMV Comfort". First, the percentage of time when the PPD (Predicted Percentage of Dissatisfaction) exceeds 10% is calculated per simulated floor level (bottom and top level) for an annual period. Secondly, additional data is extracted concerning the percentage of time feeling comfortable, too hot or too cold over a period of one year.

ITERATION PROCESS

After setting up the simulation workflow, Colibri Iterator is used to evaluate all the possible design variations. The number of design variations, i.e., the total number of simulations which were carried out are presented in *Table 3.5*.

Colibri runs a daylight simulation, an energy simulation and a thermal comfort simulation for every design version, by changing one variable at the time. The results are then written into a data.csv file, which can be uploaded online, in Design Explorer to analyse the results.

Given the large number of design variants per building, i.e., 7128 design possibilities for both buildings, which would result in a calculation time of approximately 25 days straight (5 Min/simulation), the complete iteration process was conducted only for building B (~200m) and 648 iterations were carried out for building A (~50) for a square plan layout. For building B (~200m), the performance of all four building shapes was evaluated at the bottom and at the top of the building, while changing the orientation angle and window to wall ratio, leading to a total of 3564 design iterations, which were carried out in 4 phases, taking between 1,5-4,5 days of computational simulation time. As far as building A (~50m) is concerned, only the square building shape was assessed, varying all the other parameters. It was considered unnecessary to carry out the entire iterative optimization process also for building A (~50m), because the impact of the building height on the energy performance and thermal comfort can be deduced already by comparing the results of building A (~50m) and B (~200m) for a square plan layout alone. The results are presented and evaluated in *Chapter 4*.

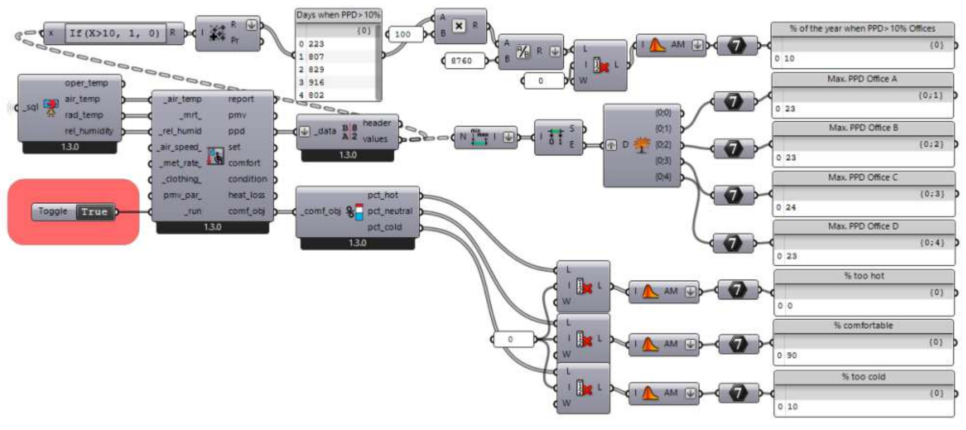


Figure 3.39: Workflow components for running the thermal comfort simulation

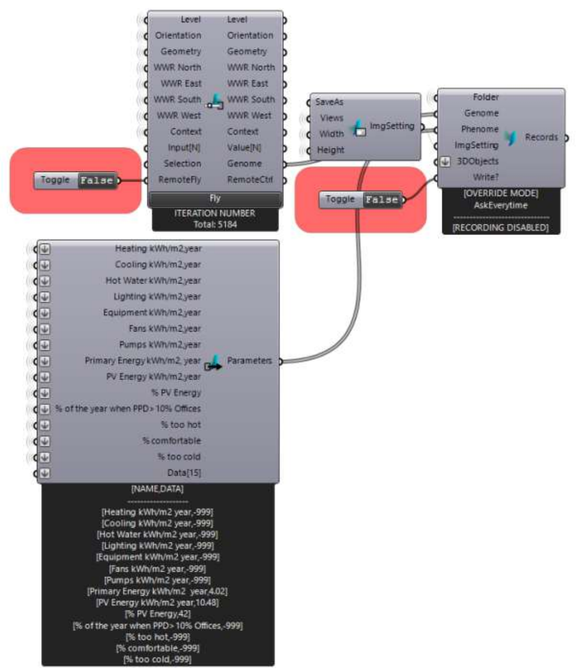
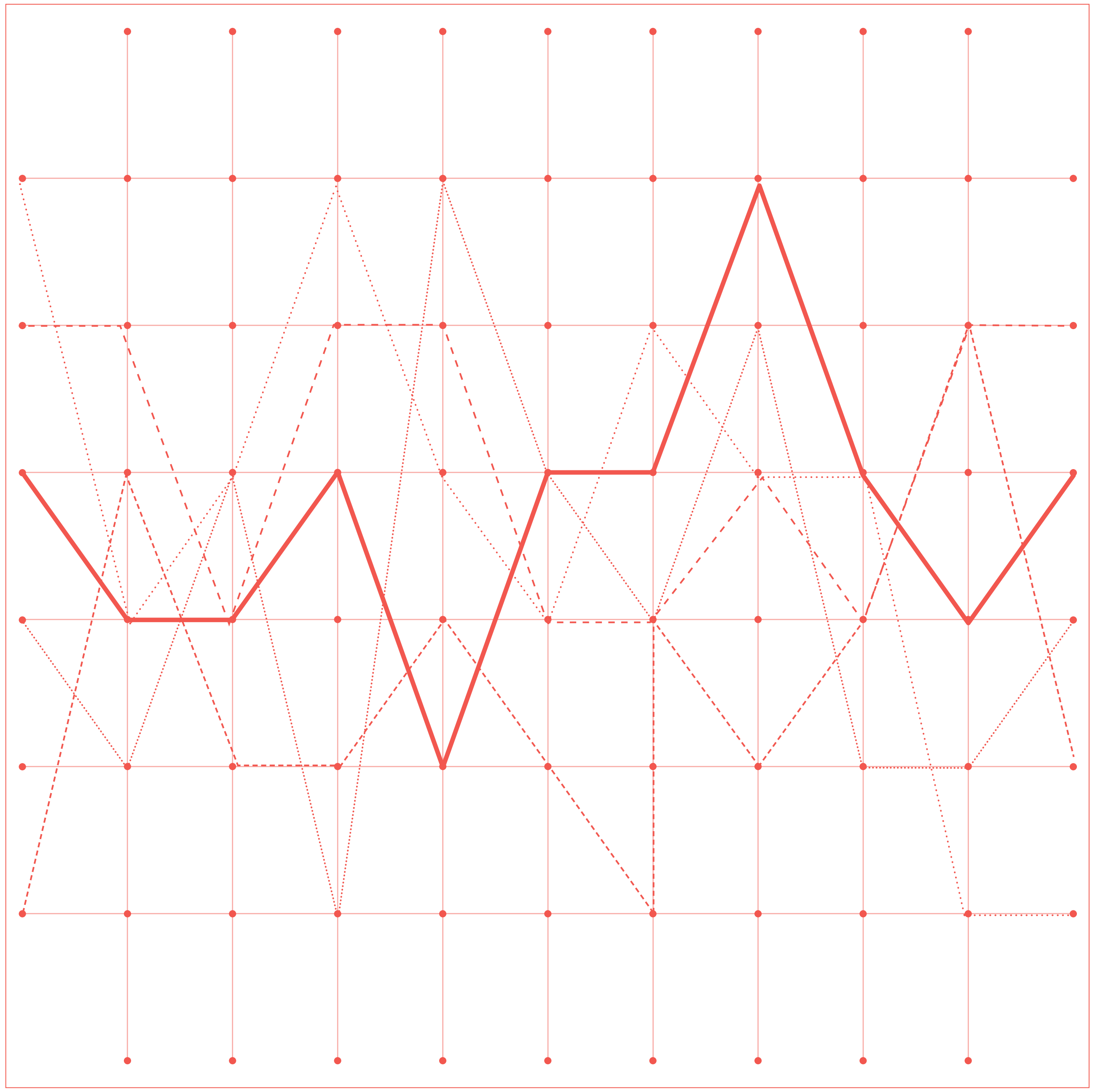


Figure 3.40: Workflow components for running the iterative process

Table 3.5: Selected variables and total number of iterations per building shape

Shapes [4]	Levels [2]	Context [2]	Orientation [1] - [4]	WWR North/East/South/West $[3^4]$	Nr Iterations
Round	Bottom,Top	Low,Mid-Rise	0°	35%, 50%, 65%	324
Square	Bottom,Top	Low,Mid-Rise	0°,45°	35%, 50%, 65%	648
Rectangular	Bottom,Top	Low,Mid-Rise	0°,45°,90°,-45°	35%, 50%, 65%	1296
Triangular	Bottom,Top	Low,Mid-Rise	0°,30°,60°,90°	35%, 50%, 65%	1296
					3564



4

RESULTS AND OPTIMIZATION

4.1 INTRODUCTION

Through the iterative design process, i.e., changing one parameter at a time, the performance of all the possible design combinations was stored as Design Explorer compatible data sets. The performance of each design strategy was quantified in terms of the energy demand and thermal comfort level in order to make the different strategies comparable.

The simulations were performed in 5 phases in order to be able to reach the purpose of this study. A complete set of simulations was performed for building B (~200m), leading to a total of 3564 design iterations, carried out in 4 phases, for each of the 4 evaluated building shapes. For building A (~50m), only one set of simulations was performed for a square building shape to evaluate the height impact on the energy performance.

The impact of the different parameter groups can be easily compared using Design Explorer. The results for building A and building B can be visualized in Design Explorer following these links:

DesignExplorer

***Open Results** of the **~200m** simulated building in in Design Explorer*

https://tt-acm.github.io/DesignExplorer/?ID=BL_3vcsjl1

https://tt-acm.github.io/DesignExplorer/?ID=BL_3BIDIdO

https://tt-acm.github.io/DesignExplorer/?ID=BL_3BOfsa8

https://tt-acm.github.io/DesignExplorer/?ID=BL_3s96bpH

***Open Results** of the **~50m** simulated building in in Design Explorer*

https://tt-acm.github.io/DesignExplorer/?ID=BL_3p8YhLj

The results of all possible design variations for a ~200m high building were quantified in *Table 4.1*. The results indicate that only 178 out of 3564 design possibilities are within the 86kWh/m².year energy threshold as far as a 200m high building is concerned. The indoor comfort values range between 69%-94%. The amount of primary energy produced by the PV panels on the roof ranges between 6%-10%, far below the 30% minimum requirement.

As far as building A (~50m) is concerned, only one set of simulations were performed for a square building shape, due to the excessive amount of simulation time involved. The results indicate that almost all design variations are within the 86kWh/m² threshold, 472 out of the 648 evaluated design possibilities. The indoor comfort level is below our aim of 90%, with values ranging between 73%-86%. The amount of primary energy produced by the PV panels on the roof ranges between 21%-28%, only 2% below the 30% minimum requirement.

To have a better understanding of how the different parameters - height, context, shape, orientation and window to wall ratio - can contribute to energy-savings and indoor comfort-improvements, the impact of each parameter will be discussed additionally on primary-energy demand and PPD-level in the sections to follow.

Table 4.1: Performance of the evauated design possibilities for building B

	Shape	Primary Energy Demand	<86 kWh/m², year	% of time comfortable	% of Primary Energy by PV
		kWh/m², year		%	%
Building B ~200m	Round	84 - 146	18 out of 324	69 - 94	6 - 10
	Square	84 - 99	28 out of 648	84 - 92	9 - 10
	Rectangular	84 - 101	59 out of 1296	81 - 93	9 - 10
	Triangular	84 - 101	73 out of 1296	81 - 91	8 - 10

Table 4.2: Performance of the evauated design possibilities for building a

	Shape	Primary Energy Demand	<86 kWh/m², year	% of time comfortable	% of Primary Energy by PV
Building A ~50m		kWh/m², year		%	%
	Square	61 - 105	472 out of 648	73 - 86	21 - 28

4.2 HEIGHT and CONTEXT

HEIGHT

The wind profile calculated in *Chapter 2.4* indicates an increase in wind speed between 0-12m/s from 2m to 50m altitude, respectively 0-23m/s from 2m to 200m altitude, depending on the orientation. This leads to higher infiltration rates, i.e., increased heat losses and prevents passive natural ventilation at higher levels due to unfavourable microclimate conditions. These changes in microclimate conditions have a noticeable impact on the energy efficiency and thermal comfort conditions at a higher level. The impact of the microclimate on the energy use is best highlighted when we look at the results of building B (~200m), as the difference in altitude between the two evaluated levels is greater.

Figure 4.3 indicates the heating and cooling loads of all the possible design strategies, at the bottom, at 4,2m height and at the top, at 193,2m height. As can be noticed, heating, as well as cooling loads tend to increase with height, and so does the mechanical ventilation load, as *Figure 4.4* indicates. Lighting loads on the other hand decrease with height due to increased solar gains *(Figure 4.5)*. Nevertheless, the primary energy use tends to increase at higher levels, as *Figure 4.6* shows. However, the increase in energy demand with height has a positive impact on the thermal comfort conditions, due to increased temperature and ventilation control.

CONTEXT

Equally important is the fact that there is strong correlation between energy use and context. Given that the impact of the two context scenarios is greater for building A (~50m), the results of this building will be evaluated. *Figure 4.7* illustrates the differences in heating and cooling loads at the bottom level (4.2m) under the two context scenarios and *Figure 4.8* at the top level (42m). As can be deduced from the graphs, heating loads tend to increase at both levels under a mid-rise context scenario, due to lower solar gains, which on the other hand has a positive impact on the cooling loads in summer.

When analysing the increase in heating and cooling loads with height under the two context scenarios, heating loads tend to increase with height only under a low-rise scenario and actually decrease with height when surrounded by mid-rise buildings. As far as cooling loads are concerned, energy used for cooling is significantly increasing at the top level under a mid-rise context scenario. This is because more heat is lost through natural ventilation and infiltration when surrounded by low-rise buildings and natural ventilation becomes less efficient to mitigate solar gains if the wind is blocked by surrounding buildings.

Figure 4.1 50m high-rise building located in a low-rise context

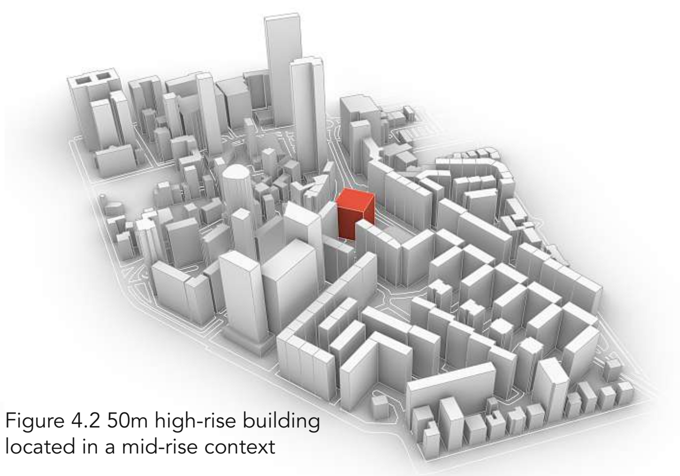


Figure 4.2 50m high-rise building located in a mid-rise context

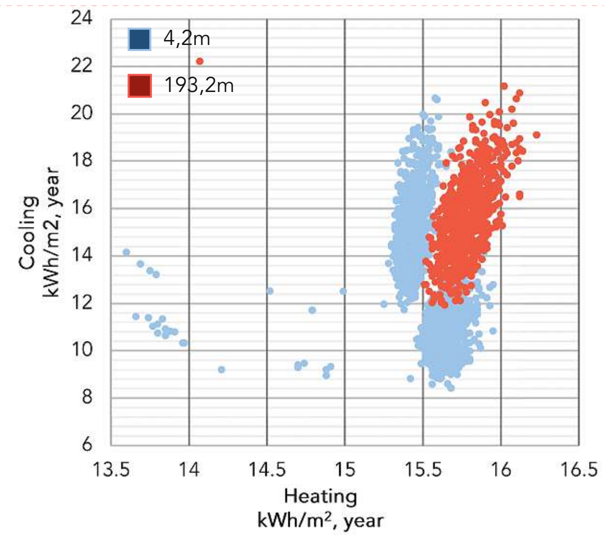


Figure 4.3: Heating and Cooling Loads

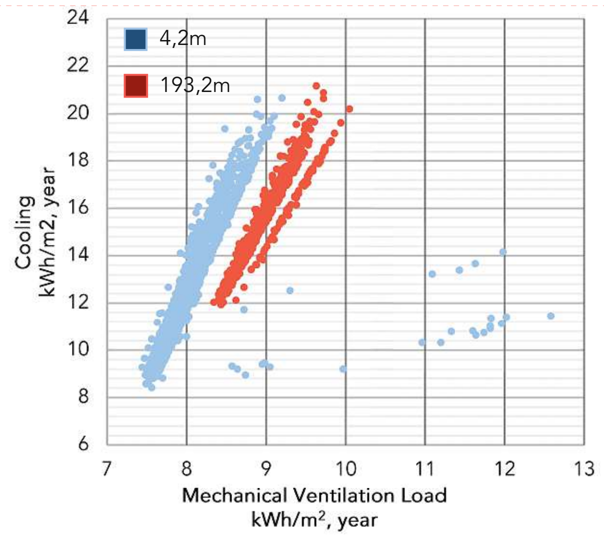


Figure 4.4: Cooling and Mechanical Ventilation Loads

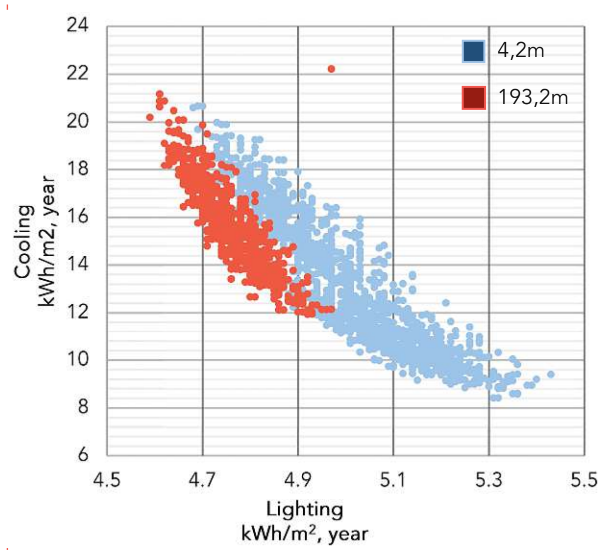


Figure 4.5: Lighting and Cooling Loads

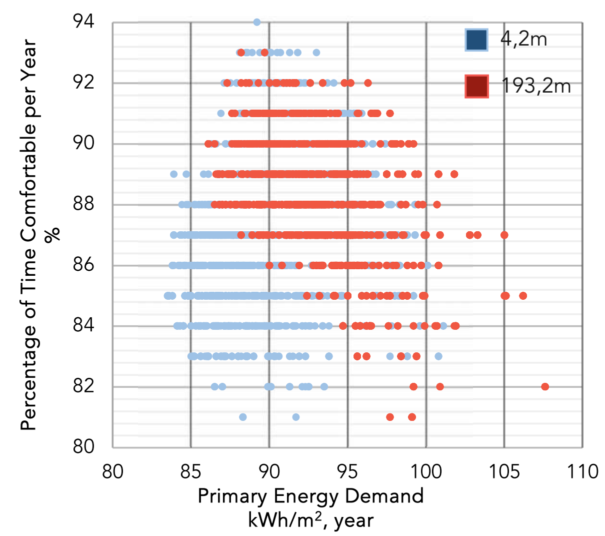


Figure 4.6: Primary energy demand and % of time comfortable

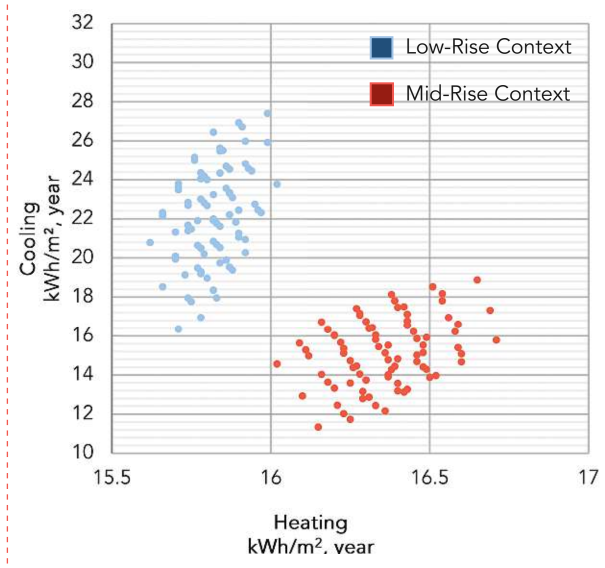


Figure 4.7: Heating and cooling loads at 4,2m

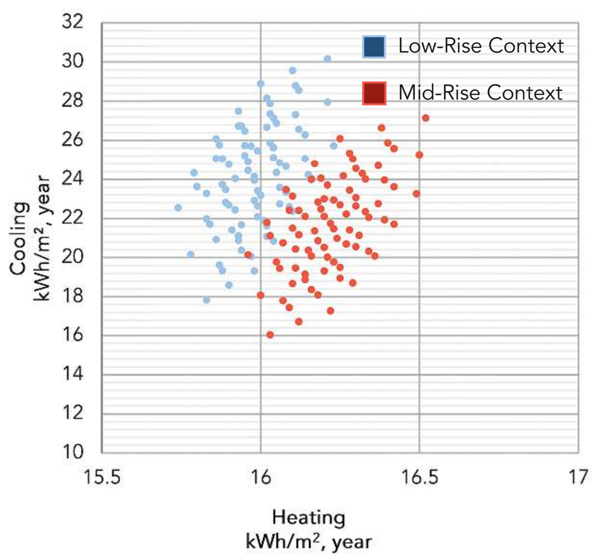


Figure 4.8: Heating and cooling loads at 42m

4.3 SHAPE and COMPACTNESS

The compactness of a building is characterized by its shape factor, i.e., the ratio between the thermal envelope and the building volume. The higher the shape factor, the larger the thermal envelope area, i.e., the greater the heat losses in winter. Several studies have already demonstrated that the more compact a building, the more efficient it is. According to *Danielski et al. (2012)*, the compactness of a building accounts for 10-20% of its final energy demand.

Looking at the shape factors of the two evaluated buildings, building A (~50m) and building B (~200m), it becomes evident that building B is more compact than building A *(Table 4.3 and Table 4.4)*. *Figure 4.10* illustrates how the difference in compactness between the two evaluated building heights is affecting the heating and cooling loads. Due to the higher shape factor, i.e., the large thermal envelope area in proportion to the building volume, building A (~50m) indicates higher heating and cooling loads per square meter.

Nevertheless, this study analyses the primary energy efficiency of the two buildings, taking into consideration also the renewable energy from PV panels, mounted on the roof. Given that the renewable energy generated by the PV panels needs to supply only 12 floors in case of building A, the resulting primary energy use is lower than that of building B, where the energy is distributed over 48 floors *(Figure 4.11)*.

As far as the plan layout is concerned, a round shape has the lowest shape factor, i.e., is the most compact building shape *(Table 4.3 and Table 4.4)*. *Figure 4.12* illustrates the impact of the shape factor on the primary energy use with height. It can be noticed that the energy demand increases with only 1.7kWh/m².year from the bottom to the top level (4.2m-193.2m) for a round building, while a less compact shape can contribute to a higher increase in energy use with altitude.

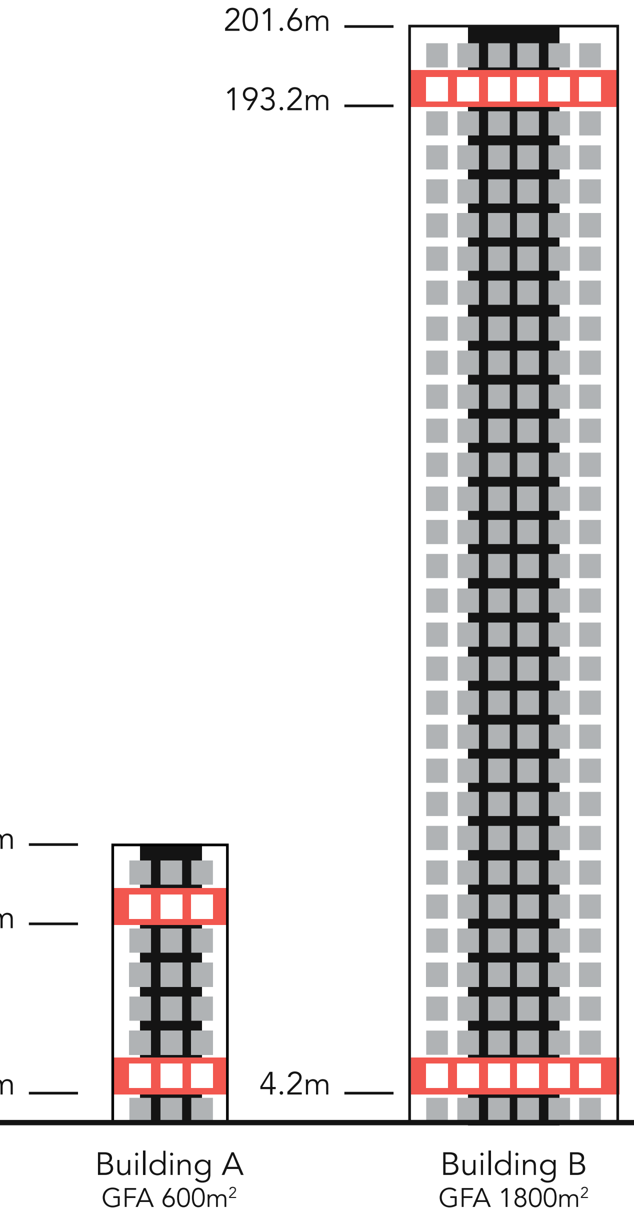


Figure 4.9 Evaluated plan layout shapes and orientation angles

Table 4.3: Shape Factors of the different building geometries for building A (~50m)

	Shape	Height	Footprint Area	Thermal Envelope Area	Volume	Shape Factor
		m	m²	m²	m³	
Building A	Round	50.4	600	5605	30240	0.19
	Square	50.4	600	6139	30253	0.20
	Rectangular	50.4	600	6438	30238	0.21
	Triangular	50.4	600	6833	30190	0.23

Table 4.4: Shape Factors of the different building geometries for building B (~200m)

	Shape	Height	Footprint Area	Thermal Envelope Area	Volume	Shape Factor
		m	m²	m²	m³	
Building B	Round	201.6	1800	21220	362880	0.06
	Square	201.6	1800	37816	362942	0.10
	Rectangular	201.6	1800	39888	362880	0.11
	Triangular	201.6	1800	42591	362880	0.12

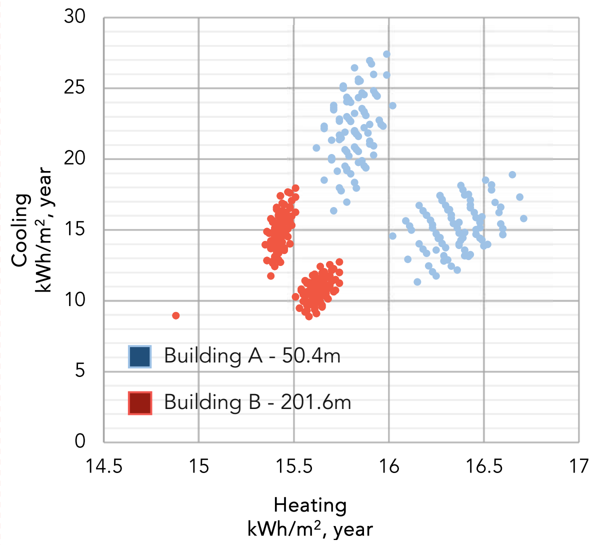


Figure 4.10: Heating and cooling loads of building A & B

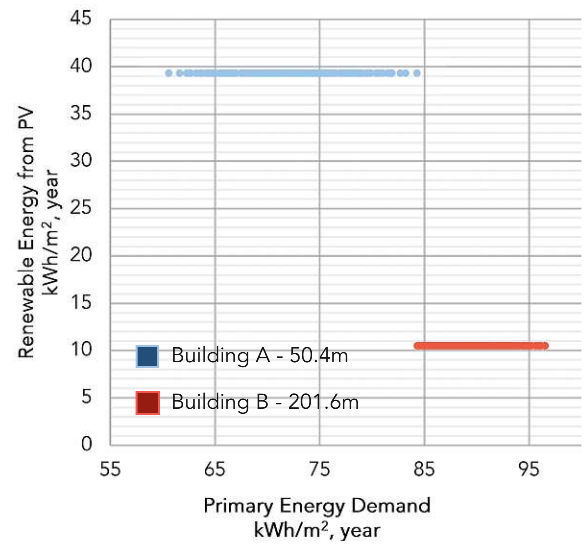


Figure 4.11: Primary energy use of building A & B
*the amount of renewable energy is sccounted for

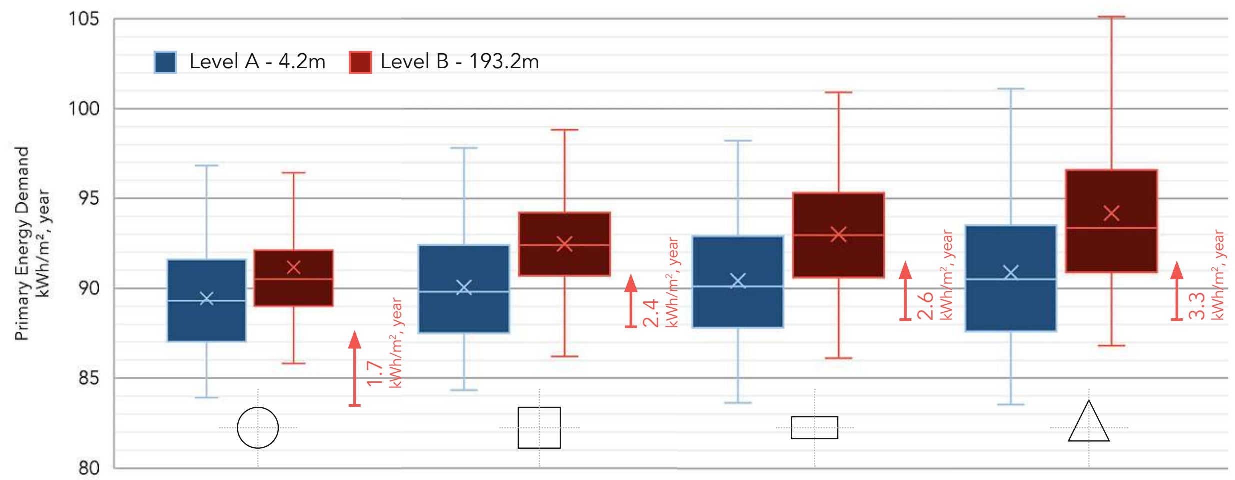
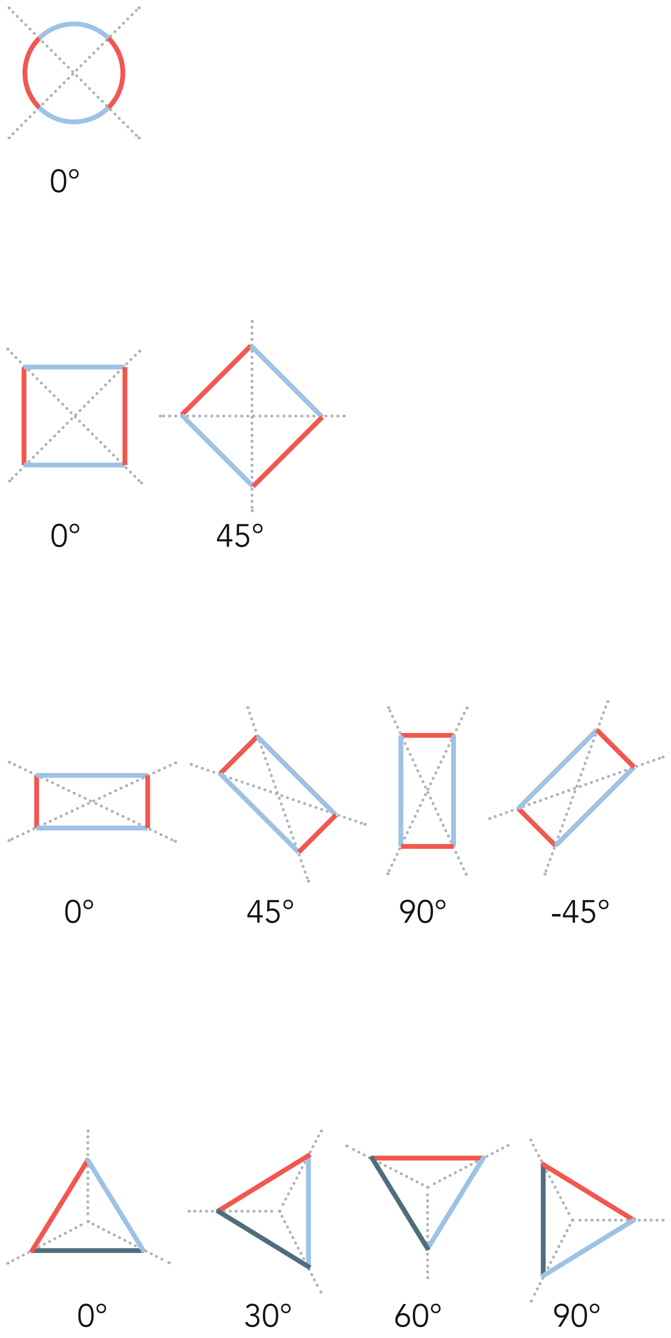


Figure 4.12: Primary energy increase with height for round, square, rectangular and triangular high-rises
*the results represent the primary energy demand at the bottom and top level of Building B (200m height)

4.4 ORIENTATION

Taking advantage of solar gains is mainly achieved through the right orientation of the building. Given that climate conditions change with height, a different orientation angle might be suited at the top of the building than at the bottom. To assess the impact of orientation with height, the effect of changing orientation was quantified based on building B (~200m), by evaluating the primary energy use at two levels, a bottom level (4.2m) and a top level (193.2m).

A round building does not allow for a specific orientation, but rectilinear and triangular shapes do. In case of a square building shape, a 0° rotation from the north seems to perform best at the bottom level, while a 45° rotation angle is more efficient at the top level under the simulated context conditions *(Figure 4.14)*. Analyzing the results for a rectangular building, it becomes evident from *Figure 4.15*, that a 45° rotation angle from the north is the optimal orientation angle at both levels. This finding differs from the results of *Raji et al. (2017)*, where an orientation angle of 0° from the north was found to be the best performing orientation angle, but for a 1:3 deep plan layout, not 1:2. The largest impact of orientation on the primary energy use was observed for a triangular building. While the difference in performance is quite insignificant at the bottom level, a 90° rotation of the top level could increase the primary energy use with ~5kWh/m².year.



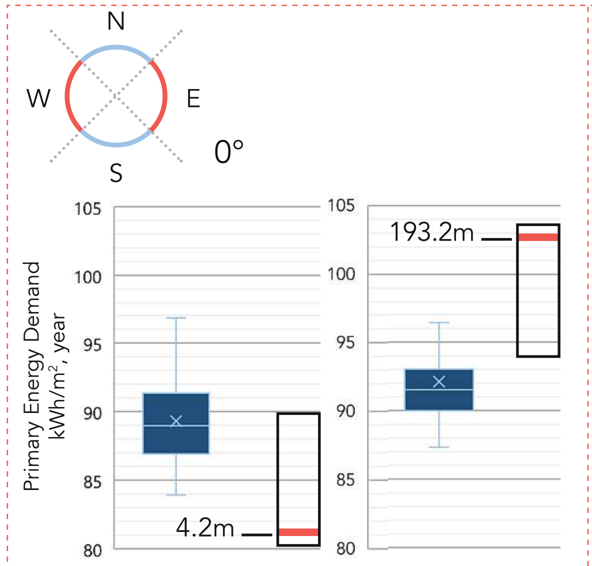


Figure 4.13: Primary energy demand at the bottom and top levels of a round ~200m high building in relation to orientation

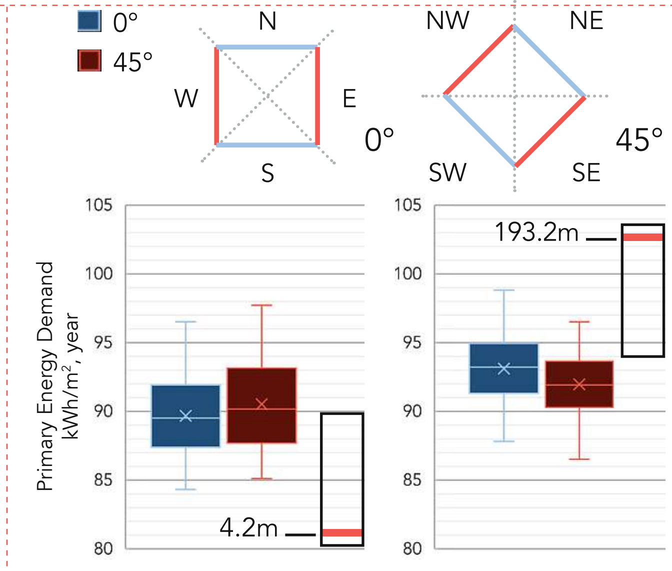


Figure 4.14: Primary energy demand at the bottom and top levels of a square ~200m high building in relation to orientation

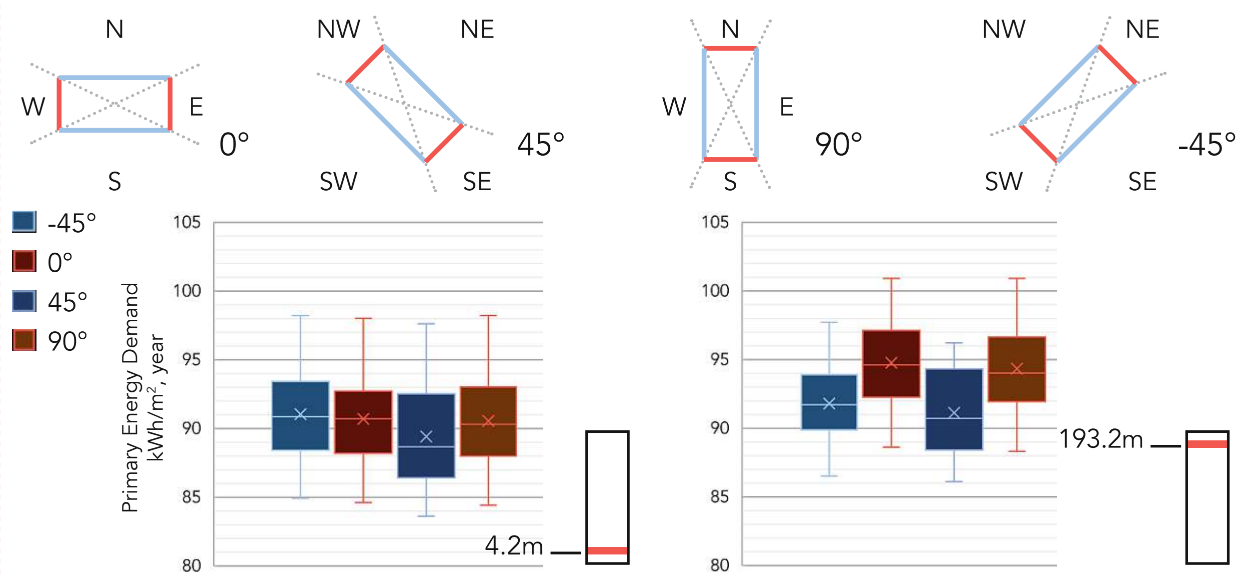


Figure 4.15: Primary energy demand at the botttom and top levels of a rectangular ~200m high-rise building in relation to

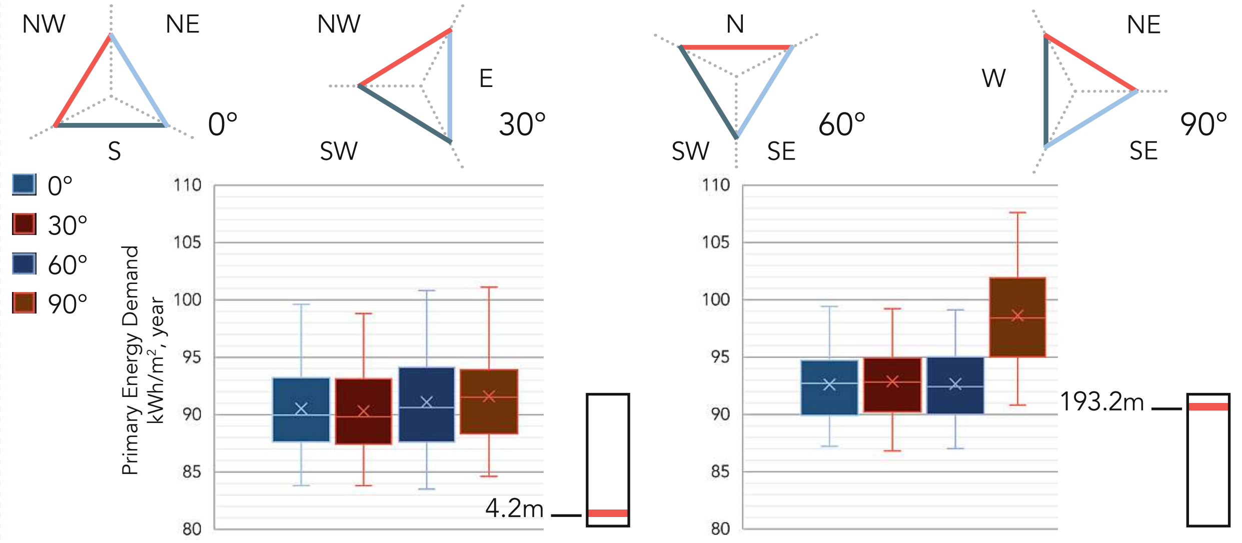


Figure 4.16: Primary energy demand at the botttom and top levels of a triangular ~200m high-rise building in relation to orientation

4.5 FACADE

As far as the facade is concerned, three different glazing percentages were investigated for all façade sides – 35%, 50% and 65%. Due to the changing microclimate conditions with height, the impact of the different glazing percentages is evaluated at the bottom and at the top level of the ~200m simulated high-rise building. In order to determine the best suited window-to-wall ratio for each façade side, the results were quantified in terms of primary energy demand, and the percentage of time feeling comfortable per year. The collected data is represented graphically in *Figures 7.4-7.47* in the *Appendix*. The performance of the three different window-to-wall ratios was evaluated for each building shape individually, in relation to orientation and height. *Tables 4.5-4.8* represent the recommended range of WWR values, where the mean primary energy demand and the mean percentage of time feeling comfortable deviate by only 1% from the optimal value in each orientation. These recommended WWRs were found to satisfy energy demand and indoor comfort conditions equally, and are not necessarily the best performing strategy in terms of energy efficiency or indoor comfort alone.

ROUND

A round shaped building has no specific orientation, but a variation in WWR is still possible by dividing the façade in each direction. It is interesting to note that a high WWR towards north, east and west was found to satisfy energy performance and thermal comfort both at the bottom and top level, whereas a lower WWR, i.e., 35% at the bottom and 50% at the top, is performing best towards south. This indicates that there is a correlation between compactness and WWR, hence if the thermal envelope area is small in proportion to the building volume, higher WWRs can be accepted.

SQUARE

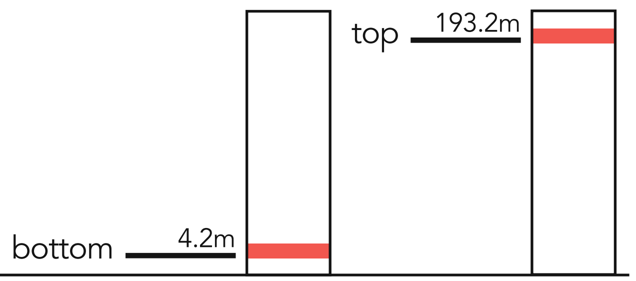
By evaluating the performance of the various WWRs for a square plan layout, it becomes evident from *Table 4.6*, that a WWR of 50% is only acceptable for a 0° rotation angle at the bottom level towards north and at the bottom and top level towards east, respectively for a 45° rotation angle at the bottom level towards north-west and south-west and at the bottom and top level towards north-east.

RECTANGULAR

As far as a rectangular plan layout is concerned, data quantified in *Table 4.7* shows, that higher WWRs are suited at the bottom for a 0° and 90° rotation angle, with low WWRs towards south and west at the top, respectively low WWRs towards north-west and south-east if the building is rotated 45° or -45°.

TRIANGULAR

Out of all the evaluated building shapes, the triangular plan layout is the less compact and therefore has the highest loss surface area in proportion to its volume. Therefore, for the sake of reducing the heat losses, the WWR needs to be reduced on all sides, with just a few exceptions, as *Table 4.8* suggests.



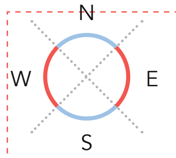


Table 4.5: Recommended WWR at the botttom and top levels of a round ~200m high-rise building for each facade side, depending on the orientation of the building

Orientation	North		East		South		West	
	bottom	top	bottom	top	bottom	top	bottom	top
No Orientation	35-50%	50-65%	35-65%	50-65%	35%	50%	35-65%	35-50%

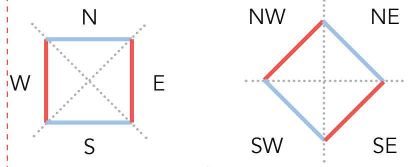


Table 4.6: Recommended WWR at the botttom and top levels of a square ~200m high-rise building for each facade side, depending on the orientation of the building

Orientation	North		East		South		West	
	bottom	top	bottom	top	bottom	top	bottom	top
0°	35-50%	35%	35-50%	35-50%	35%	35%	35%	35%
	North-West		North-East		South-East		South-West	
	bottom	top	bottom	top	bottom	top	bottom	top
45°	35-50%	35%	35-50%	35-50%	35%	35%	35-50%	35%

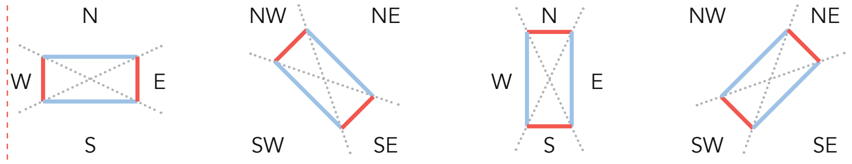
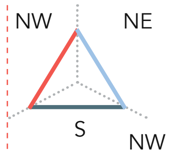
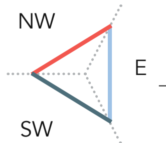


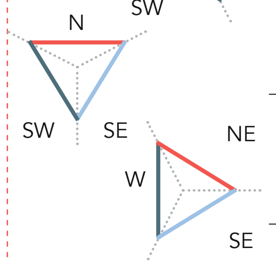
Table 4.7: Recommended WWR at the botttom and top levels of a rectangular ~200m high-rise building for each facade side, depending on the orientation of the building

Orientation	North		East		South		West	
	bottom	top	bottom	top	bottom	top	bottom	top
0°	35-50%	35%	35-50%	35-50%	35%	35%	35-50%	35%
90°	35-50%	35-50%	35-50%	35%	35-50%	35%	35%	35%
	North-West		North-East		South-East		South-West	
	bottom	top	bottom	top	bottom	top	bottom	top
45°	35%	35-50%	35%	35-50%	35%	35%	35-65%	35-65%
-45°	35%	35%	35-50%	35-50%	35%	35%	35-50%	35-50%

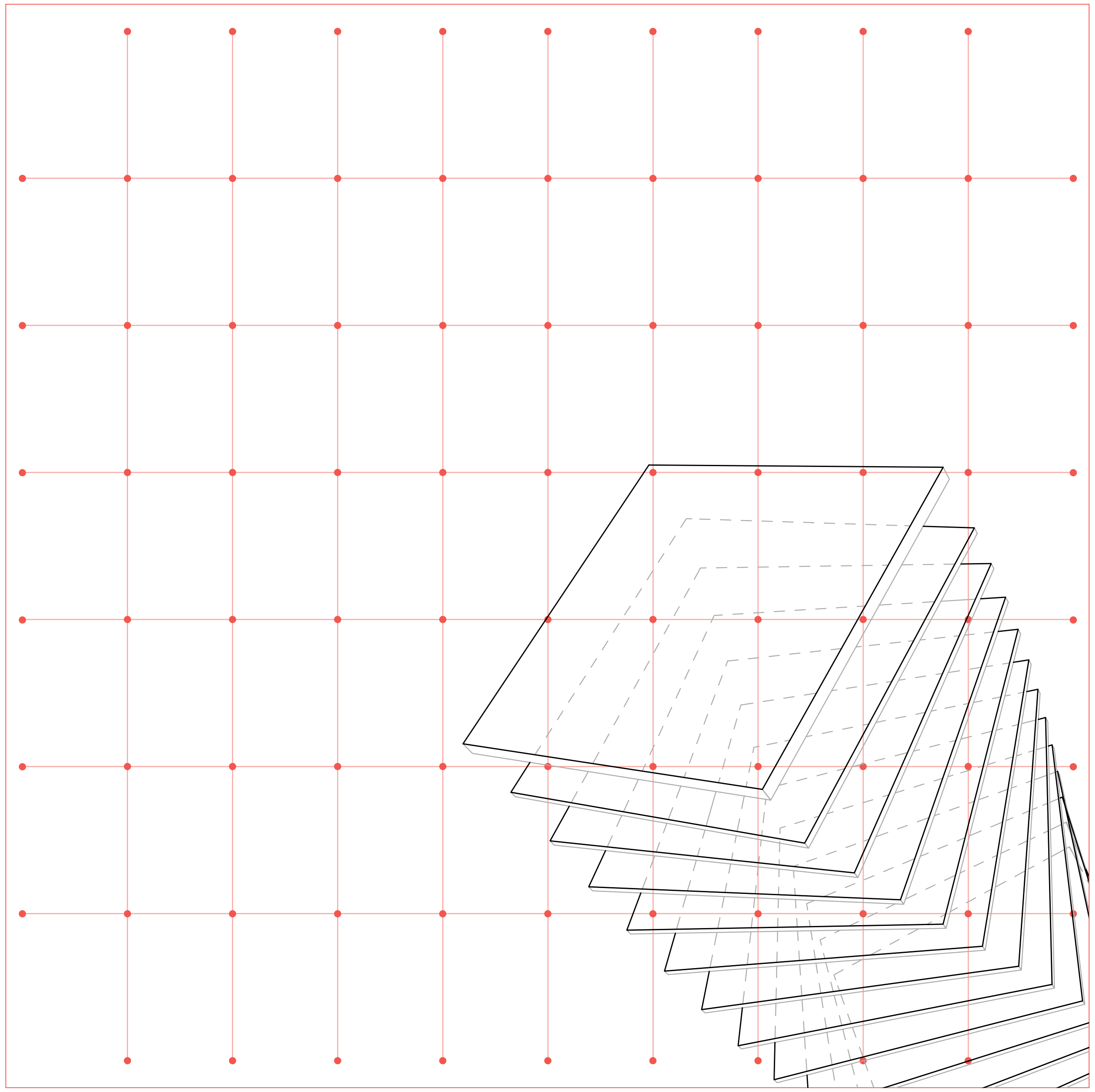
Table 4.8: Recommended WWR at the botttom and top levels of a triangular ~200m high-rise building for each facade side, depending on the orientation of the building







Orientation	North-West		North-East		South	
	bottom	top	bottom	top	bottom	top
0°	35%	35%	35-50%	35%	35%	35%
	North-West		East		South-West	
	bottom	top	bottom	top	bottom	top
30°	35%	35%	35%	35-50%	35%	35%
	North		South-East		South-East	
	bottom	top	bottom	top	bottom	top
60°	35-50%	35%	35%	35%	35%	35%
	North-East		South-East		West	
	bottom	top	bottom	top	bottom	top
90°	35%	35%	35%	35%	35%	35%



5 Design Proposal

DESIGN PROPOSAL

In order to decide on the most beneficial preliminary design for our area of study, the results were analyzed in terms of primary energy consumption and thermal comfort for a 50m high-rise building, which would fit well within the existing surrounding low-rise context.

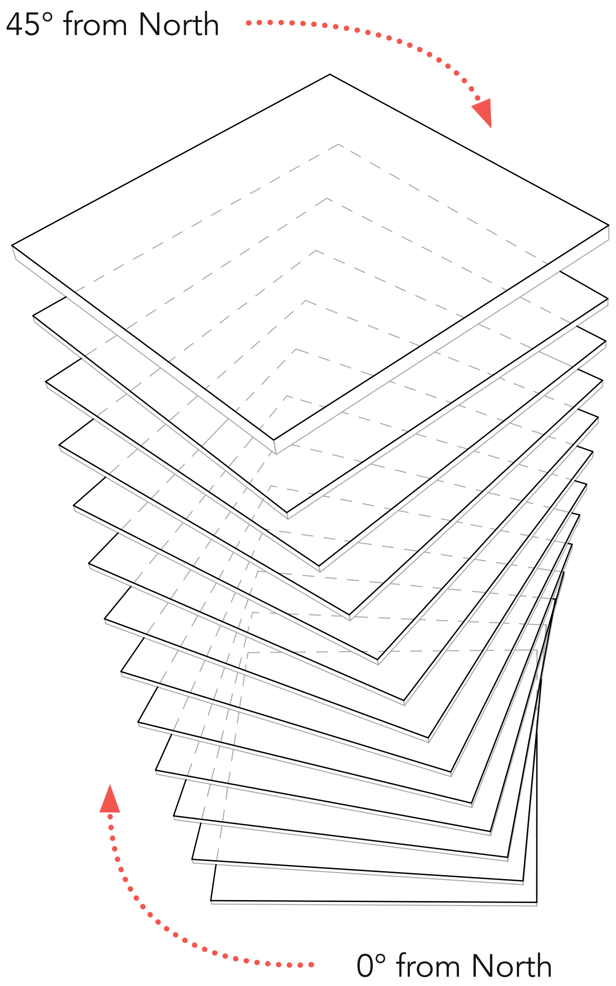
SHAPE
In terms of geometry, a circular building shape would be the most efficient due to its compactness. However, a circular building shape is not the most space efficient when it comes to the effective use of space. Therefore, a square building shape was considered to be the best choice in terms of energy performance and floor area efficiency.

ORIENTATION
As pointed out in *Chapter 4*, an orientation of 0° was found to be the most energy efficient for the bottom part of a high-rise building, while a 45° rotation is performing better towards the top.

WWR
In order to decide on the most beneficial window to wall ratio in every orientation, the results of the iterative design process for building B (~50m) were analyzed using Design Explorer based on the primary energy consumption and thermal comfort. As mentioned in *Chapter 4*, the primary energy demand tends to increase when the shape factor increases. A 50m square building with a footprint area of 600m² has a shape factor of 0.20, which is double than that of a 200m building with a footprint area of 1800m², which has a shape factor of 0.10, i.e., is more compact. In addition, it becomes evident that the total energy consumption has a conflicting influence over thermal comfort.

Due to the less compact geometry, the area of the thermal envelope is large, and therefore, the heat losses in winter are greater. When analyzing the results, a maximum of 86% indoor comfort level can be achieved with a high WWR towards the south. However, this has a negative impact on the energy performance. In order to prevent heat losses and achieve a high thermal comfort level, a WWR of 35% is suited best in all orientations. A larger WWR of 50% towards the south would improve the thermal comfort level by 1%, but increase the primary energy demand by approximately 3,5 kWh/m².year.

Given that 158 out of the 162 design possibilities for a square ~50m building are within the 86 kWh/m².year energy threshold, it was considered worthwhile to improve the thermal comfort level by increasing the WWR towards the south, which would lead to a slightly higher primary energy need.



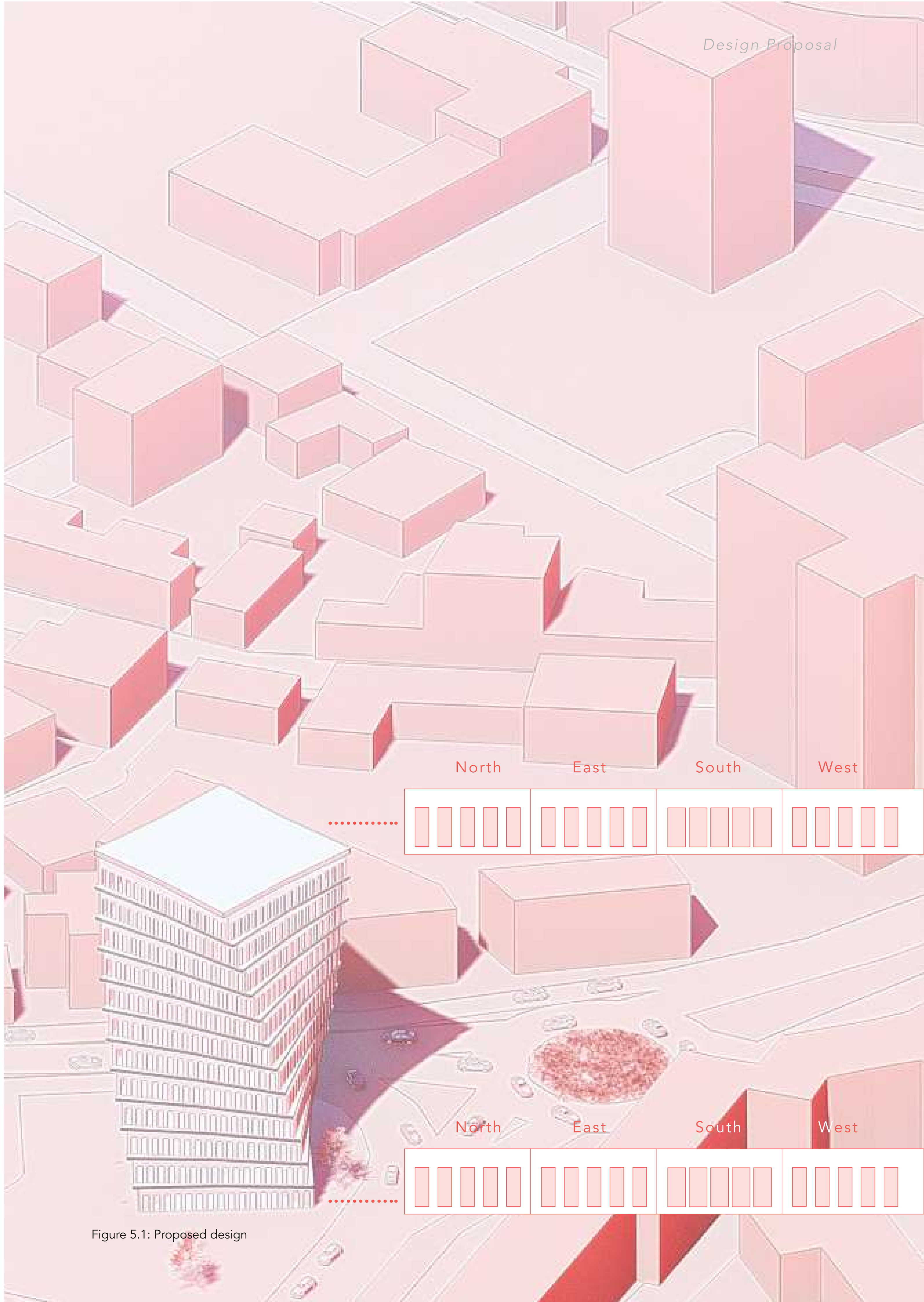


Figure 5.1: Proposed design

REDESIGN SOLUTION
Bottom Level (4,2m) / Top Level (42m)

SELECTED CHARACTERISTICS:
Context: Low
Bulding Height: 50m
Shape: Square
Orientation 0 / 45°
WWR North : 35%
WWR East : 35%
WWR South : 50%
WWR West : 35%

PROPERTIES:
Glazing : Triple Glazing
(U-value=0,6 W/m²K / SHGC=0,5 / VLT=0,7)
Shade : Interior Blinds
Natural Ventilation: Tilting Windows
Mechanical Ventilation, Heating and Cooling: DOAS system in combination with a ground source water heat pump (COP=3,6 / EER=12)
Insulation Performance of the Exterior Walls: 4,5 m²K/W

PERFORMANCE:
Bottom Level (4,2m) / Top Level (42m)

Cooling : 18,5 / 20,2 kWh/m², year
Heating : 15,7 / 15,8 kWh/m², year
HotWater : 12,6 / 12,6 kWh/m², year
Lighting : 4,7 / 4,6 kWh/m², year
Equipment : 15,4 / 15,4 kWh/m², year
Fans : 8,9 / 9,1 kWh/m², year
Pumps : 7,3 / 10,5 kWh/m², year

Primary Energy : 68,9 / 77,7 kWh/m², year
Primary Energy by PV: 39,3 / 39,3 kWh/m², year
% Renewable Energy by PV: 27% / 25%
% of time comfortable : 86% / 86%
% of time too hot : 1% / 1%
% of time too cold : 14% / 14%

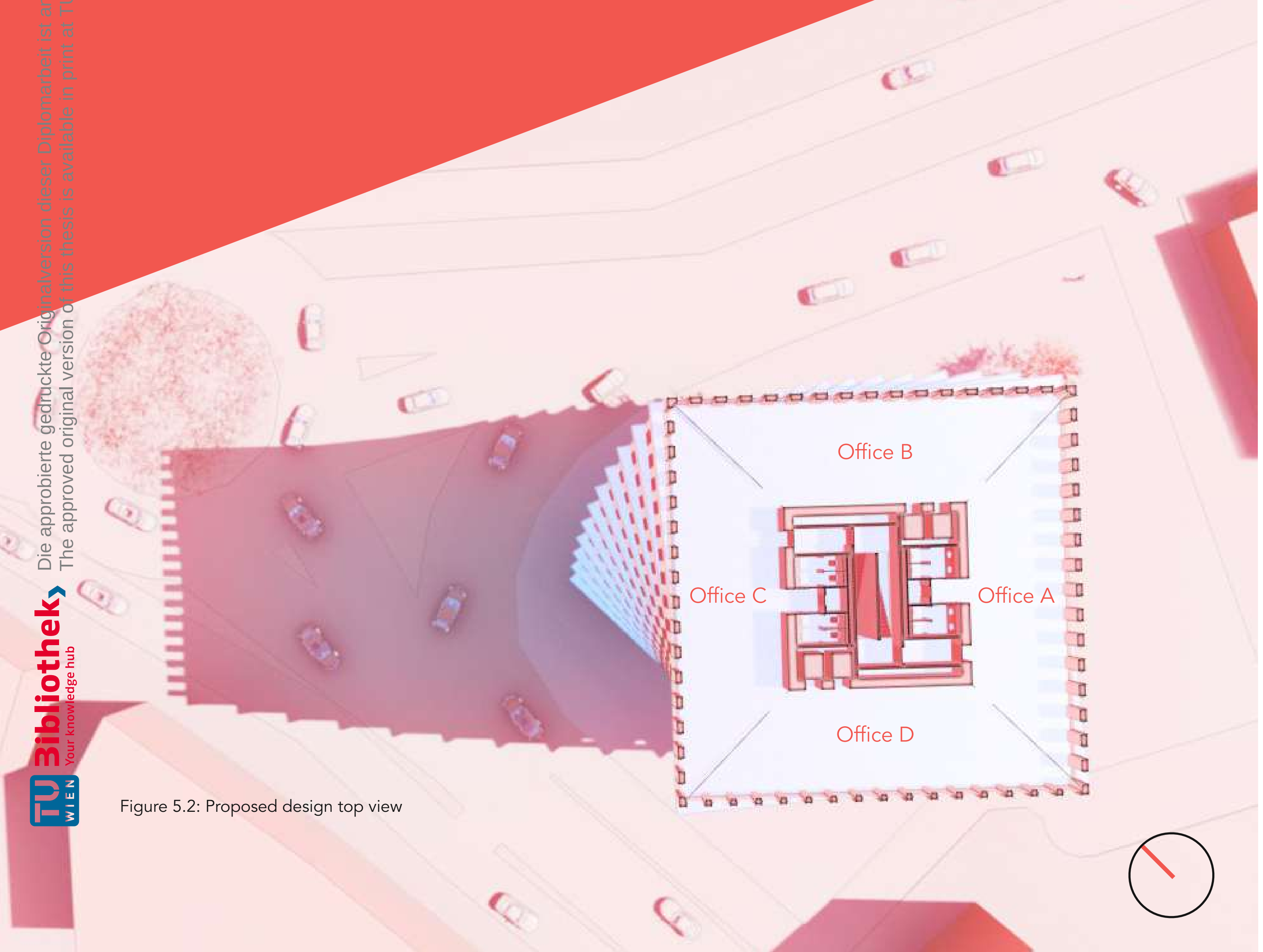


Figure 5.2: Proposed design top view

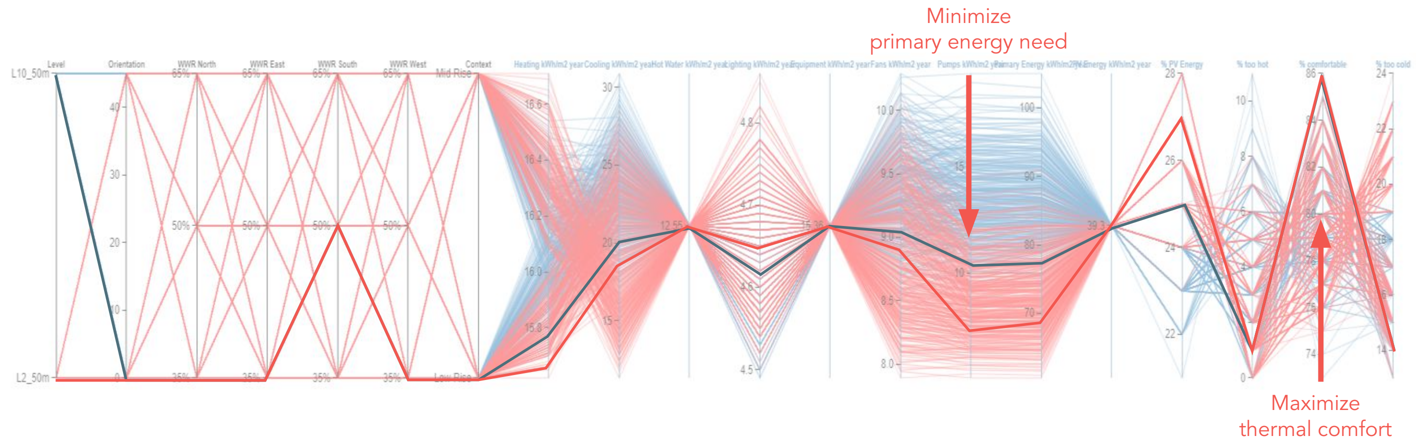


Figure 5.3: Parallel coordinates chart of the design iteration selection for a 50m high building by adjusting the range toward the objectives - low energy demand, high thermal comfort

Figure 5.3 shows the selection process of the design proposal at the two extreme levels according to the defined objectives, i.e., minimizing the primary energy demand while maximizing the thermal comfort level.

For the chosen design proposal, the indoor comfort conditions were analysed more in detail for each office space in order to determine where the problem lies for not reaching the 90% satisfaction rate.

Figure 5.4-5.7 represent the predicted percentage of dissatisfaction (PPD) for each office space. The percentage of dissatisfaction is represented hourly over a period of one year. The results indicate a higher dissatisfaction rate during winter, as suspected already from the simulation results, which indicate that throughout 14% of the year, people are feeling slightly too cold. However, the higher discomfort level is recorded after or before working hours. Given that the occupancy during 6pm and 6am is very low, the lower comfort levels are not of a concern.

The lower comfort level, which was recorder outside the office hours is also a result of the reduced amount of heating which was set to vary based on the occupancy.

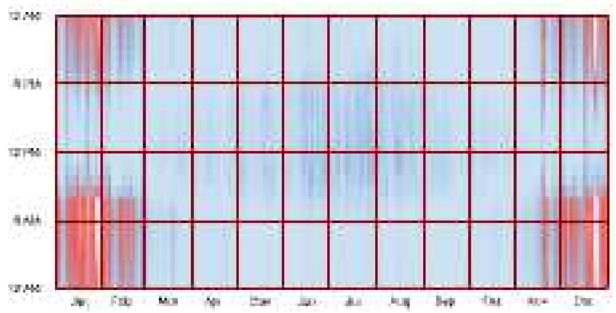


Figure 5.4: PPD Office A

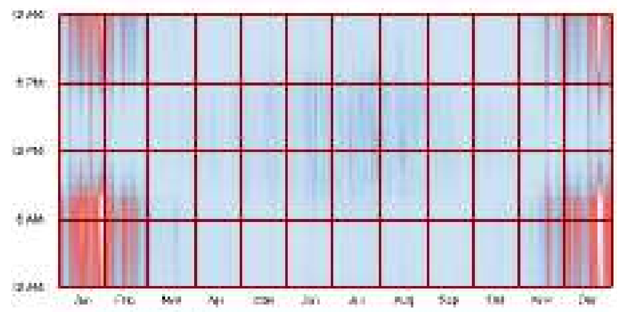
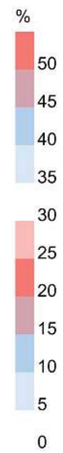


Figure 5.5: PPD Office B



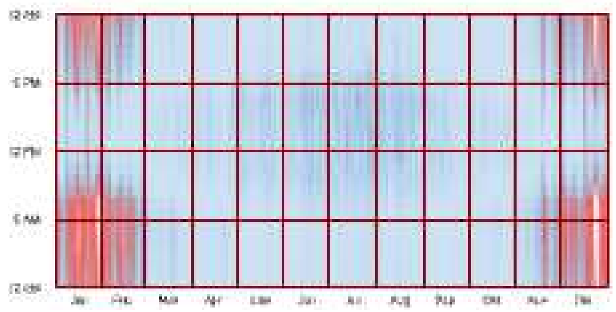


Figure 5.6: PPD Office C

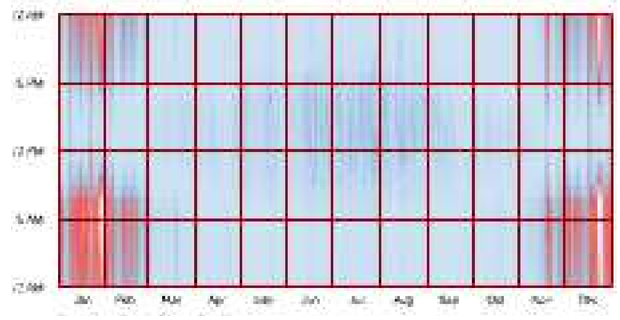
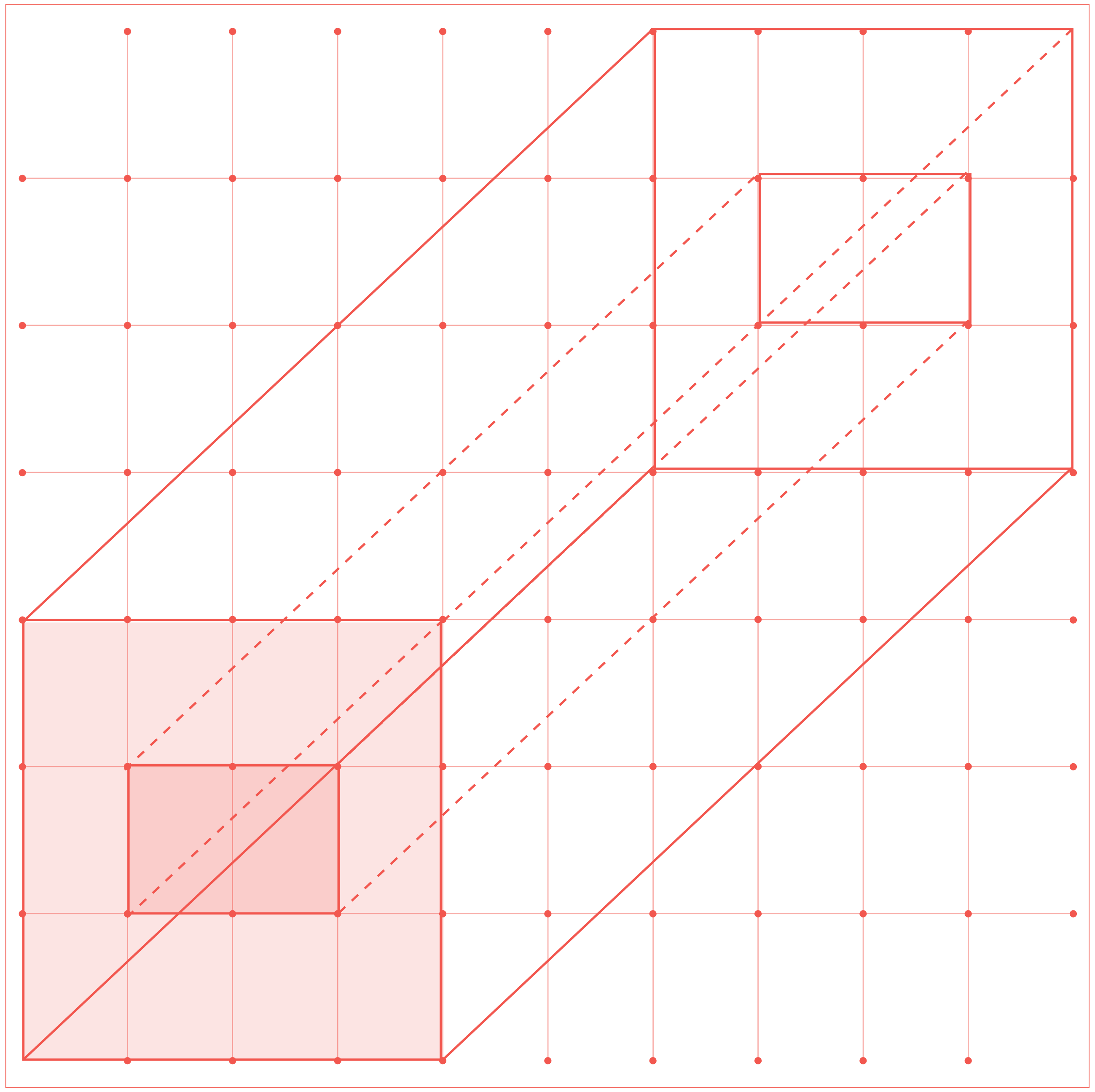


Figure 5.7: PPD Office D

The proposed design resulted purely from a energetical point of view, while providing a pleasant indoor comfort level. In spite of this, the optimization process led to an architecturally intriguing, energy efficient building which would fit well within the surrounding context. The following representations show the view from the two main boulevards, Vasile Milea Boulevard (left) and Calea Dumbravii (right).

Figure 1: View from Vasile Milea Boulevard

Figure 1: View from Calea Dumbravii



6

Discussion and Conclusion

6.1 DISCUSSION

This study shows the potential of an optimized preliminary design for an office high-rise building located in a temperate climate. The aim of this research paper was to answer the following question: *"To what extent are energy regulations a limitation to the construction of a high-rise office building in Romania and which changes can be proposed by means of parametric optimization in order to reach the desired height and the required energy output?"*

In order to answer this main research question, an iterative optimization process was adopted using Grasshopper, which made it possible to simulate the performance of a large number of design combinations and compare them easily in Design Explorer. Through the literature review, the most influential design parameters were filtered out, which served as variables in the optimization process – height, context, shape, orientation and window to wall ratio. Through the optimization process, the following aspects have become apparent:

1. There is a clear relationship between height and energy consumption. The energy consumption was found to increase with +0,4 kWh/m^2.year with every additional 50m for circular buildings, while less compact building shapes like square, rectangular or triangular plan layouts recorded an energy increase of +0,6 kWh/m^2.year, +0,65 kWh/m^2.year, respectively +0,8 kWh/m^2.year with every additional 50m of building height.

2. Heating loads increase under a mid-rise surrounding context, while cooling loads decrease. With height, heating loads decrease from bottom towards the top when surrounded by mid-rise buildings. Cooling loads on the other hand increase significantly at the top level under a mid-rise context scenario, in comparison to a low-rise context scenario where heating and cooling loads increase just slightly from one level to another.

3. The orientation of the building is very important and can add up to ~5kWh/m^2.year if the wrong orientation angle is chosen. One interesting finding is that a 0° angle from the north is best suited at the bottom of a square building, while a 45° angle is performing best towards the top in case of a ~200m high-rise. For a 1:2 elongated floor plan, a 45° orientation angle showed the best results. As far as a triangular building is concerned, 0°, 30° and 60° are acceptable orientations.

4. There is a clear relationship between WWR and compactness. The lower the shape factor, i.e., the more compact a building is, the higher the glazing ratio can be.

5. A change in facade with orientation is essential in order to control the amount of solar gains in summer, respectively heat losses in winter. A change in façade with heigh is beneficial if the building is higher than 50m and the surrounding context is predominantly lower than the building.

6. Natural ventilation is less feasible at high altitudes because of the unfavorable microclimate conditions. This leads to higher mechanical ventilation, heating and cooling loads at the top levels. It is worth mentioning that for this study, heating, cooling and mechanical ventilation were conditioned to the degree of occupancy, which means that heating an cooling are mainly activated only during working hours. Therefore, a higher percentage of dissatisfaction was recorded outside working hours, when the office spaces are occupied at a very low capacity. In order to prevent any discomfort levels, heating and cooling hours should be extended outside working hours, which would imply however higher heating and cooling loads, or user-controlled.

6.2 LIMITATIONS

The most important limitation of an iterative optimization process as such is the substantial amount of computational time involved in relation to the number of variables selected and the complexity of the simulation workflow. This study analyses the impact of only a few variables which were identified as having the most significant influence based on research papers mentioned in the literature review. Nevertheless, the selected variables still led to a high number of 3564 different design combinations for one building. Due to time constraints, the 3564 simulations were performed only for the ~200m high building, and for the ~50m building, only 648 simulations were performed for a square plan layout.

In addition, simplifications were necessary to be made in terms of plan layout by simplifying the floor plan and dividing the office spaces by 'air walls'. This was necessary because the glazing ratio cannot be calculated for a donut-shaped geometry with a core in the middle and an open floor plan around.

The simulations were performed at two extreme levels. If more intermediate levels would be evaluated, it could be that a different orientation or WWR would be suited at the middle part of the building.

With the current applied methodology, the simulation workflow was reduced to only a few parameters. If more WWRs or orientation angles would have been assessed, the outcome could lead to better performance results. However, a longer period of time would have been needed for the calculation.

6.1 FURTHER RESEARCH

This study could serve as a starting point for further studies. This could entail broadening the variable spectrum of this study and analyze different aspects of high-rise buildings. This study makes evident that the following aspects have room for improvement:

- Assessing the impact of the selected design parameters for residential high-rises, which are a rather night-heating dominated typology
- Investigating the performance of passive design strategies without the use of a heat pump.
- Simulating the impact of the selected design parameters in terms of energy performance and thermal comfort with full user control
- Investigating whether a change in facade with height is beneficial if the high-rise building is located in a much denser urban context
- Performing the same optimization workflow under different climatic conditions
- Assessing the impact of a greater range of parameters and variables
- Calculating the embodied energy of the assessed building before and after the optimization process

Although further investigations are needed, the present study contributes to a better understanding of how energy performance is affected by different design parameters.

6.2 CONCLUSION

As an overall conclusion about the future design of nZEB high-rises, it can be stated that the preliminary-design plays an important role to reduce the energy demand, produce energy and improve indoor comfort conditions. In order to reach the scope of this study, an integrated design workflow was developed to assess the performance of different influential design parameters, which were found to have a significant impact on the energy performance of a high-rise. Through the iterative design workflow, several parameter combinations were assessed and the results were quantified by minimizing the primary energy demand and maximizing the thermal comfort level.

This study has investigated whether the primary energy limit of 86kWh/m^2.year set for Romania is a limitation to the construction of an office high-rise building and whether this threshold can be met for a ~200m high building. Based on the results of the optimization process, only 178 out of 3564 design possibilities are within the 86kWh/m^2.year energy threshold as far as a ~200m high building is concerned. This is because height contributes considerably to the efficiency/inefficiency of the building and energy performance decreases with altitude due to the harsh environmental conditions. But another important aspect is that the area dedicated for generating energy is small relative to the building height for tall buildings reaching ~200m, the percentage of renewable energy generated by PV panels on the roof ranging between 6-10%, far below the 30% minimum requirement. This indicates that energy generating units are an indispensable facade element for high-rises if energy generating targets are to be met.

The context also affects the high-rise performance. More obstruction of the facades, i.e., higher surrounding buildings results in higher heating loads and lower cooling loads.

Based on the results of the optimization, certain design guidelines are to be followed for an early-stage design in order to be able to come within a closer range to the implemented energy benchmarks.

The orientation of the building determines the amount of exposure on the facade. A 0° angle was found to perform best at the bottom of a square building and a 45° angle at the top. A rectangular building should be orientated at an angle of 45°, with the long facade facing south-west. A triangular shaped building can be orientated at 0°, 30° or 60°.

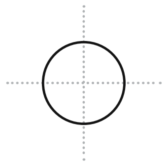
In order to minimize the loss surface area, the building shape should be as compact as possible. The more compact the building shape, the higher also the WWR can be. Unless the building is round, glazing ratios should be kept between 35-50%. It is essential that the glazing ratio varies in each orientation and changes even with height. A more precise indication on what WWRs perform best at the bottom and at the top of a ~200m building, based on the building orientation can be found in Tables 4.5-4.8 of Chapter 4.

High-rises in particular tend to consume more energy per square meter with height, so their environmental impact is usually greater that of low-rise buildings. For this reason, designing high-rises which comply to future energy-efficiency targets will be quite challenging in the near future. The developed workflow in this research is meant to assists architects in finding an energy-saving near-optimal solution for an early-stage office high-rise design in a temperate climate. Based on the results of the optimization process, the primary energy demand of an office high-rise building located in a temperate climate can be reduced with ~24kWh/m^2.year by optimizing the shape, orientation and window to wall ratio alone.

7 Appendix

Table 7.1: GFA and core area of 15 circular high-rises
*the following data is a rough approximation

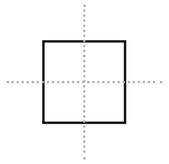
		Height	Footprint GFA	Core Area	GFA without Core
		m	m²	%	%
1.	Shanghai Tower	632	3700	82%	18%
2.	Chengdu Greenland Tower	468	2830	72%	28%
3.	China Resource Center	393	3220	73%	27%
4.	Ciel Tower	365	1280	74%	26%
5.	Millenium Tower	202	910	78%	22%
6.	St. Mary Axe	179	2210	70%	30%
7.	Torre Agbar	144	1110	83%	17%
8.	Sky Tower	137	1100	76%	24%
9.	RWE Headquarters	127	800	85%	15%
10.	Z-Tower	123	1020	78%	22%
11.	Westhafen Tower	112	1130	80%	20%
12.	Hercules Tower	100	900	78%	22%
13.	Central Tower	85	380	70%	30%
14.	Axel Towers	67	620	76%	24%
15.	Menara Mesiniaga	60	350	74%	26%



15%-20%	4
21%-25%	6
26%-30%	5
31%-35%	0

Table 7.2: GFA and core area of 15 square high-rises
*the following data is a rough approximation

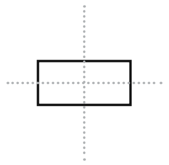
		Height	Footprint GFA	Core Area	GFA without Core
		m	m²	%	%
1.	Ping An Finance Center	599	3110	66%	34%
2.	Godin Finance 117	597	3810	72%	28%
3.	Taipei 101	508	3250	82%	18%
4.	International Commerce Center	484	3264	69%	31%
5.	Shum Yip Upperhills Tower	388	2940	67%	33%
6.	Salesforce Tower	326	2480	73%	27%
7.	Zhongzhou Holdings Financial Tower	301	2100	75%	25%
8.	The Evolution Tower	246	1410	68%	32%
9.	Omniturm	190	1530	80%	20%
10.	Singapore Land Tower	190	1600	76%	24%
11.	Tour St Gobain	179	1650	72%	28%
12.	G-Tower	150	1880	77%	23%
13.	Uptown Munchen	146	1260	83%	17%
14.	Speeturm	70	780	85%	15%
15.	Astra Turm	50	680	76%	24%



15%-20%	4
21%-25%	5
26%-30%	3
31%-35%	3

Table 7.3: GFA and core area of 15 rectangular high-rises
*the following data is a rough approximation

		Height	Footprint GFA	Core Area	GFA without Core
		m	m²	%	%
1.	KK100	442	2740	68%	32%
2.	John Hancock Center	344	4060	78%	22%
3.	Neva Towers	297	2800	78%	22%
4.	Beijing Greenland Center	260	2080	72%	28%
5.	FKI Tower	246	2190	80%	20%
6.	Isreli Sarona Tower	238	2370	67%	33%
7.	Hearst Tower	182	1810	85%	15%
8.	Huishang Bank	180	2565	70%	30%
9.	Zhongzhou Holdings Financial Center	158	1440	85%	15%
10.	Marienturm	155	1275	72%	28%
11.	Gate 2	116	1190	83%	17%
12.	Guoyin Minsheng Financial Building 2	109	1800	85%	15%
13.	The Lee Towers	93	1610	80%	20%
14.	Twin City Tower	89	1290	80%	20%
15.	The EXO Building	73	700	83%	17%

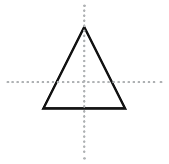


1:1.2 - 1:2

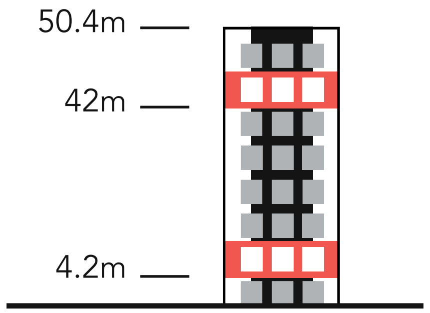
15%-20%	8
21%-25%	2
26%-30%	2
31%-35%	3

Table 7.4: GFA and core area of 15 triangular high-rises
*the following data is a rough approximation

		Height	Footprint GFA	Core Area	GFA without Core
		m	m²	%	%
1.	Busan Lotte Tower	510	2690	73%	27%
2.	Wuhan Greenland Center	475	3280	68%	32%
3.	Zifeng Tower	450	2740	72%	28%
4.	Guangzhou IFC	438	2150	76%	24%
5.	Federation Tower 1	374	2880	83%	17%
6.	Commerzbank Tower	258	2075	75%	25%
7.	Federation Tower 2	242	2470	83%	17%
8.	Nanchang Sinic Center	210	2500	80%	20%
9.	Al Bidda Tower	197	1230	73%	27%
10.	Trilogy Seafront West Office Tower	190	960	78%	22%
11.	Torre Ibedrola	165	1840	70%	30%
12.	Kolntriangle	103	780	78%	22%
13.	Orbi Tower	102	1040	85%	15%
14.	Sthlm	102	1230	84%	16%
15.	Campustower Hafencity	60	600	80%	20%



15%-20%	6
21%-25%	4
26%-30%	4
31%-35%	1



Building A
GFA 600m²

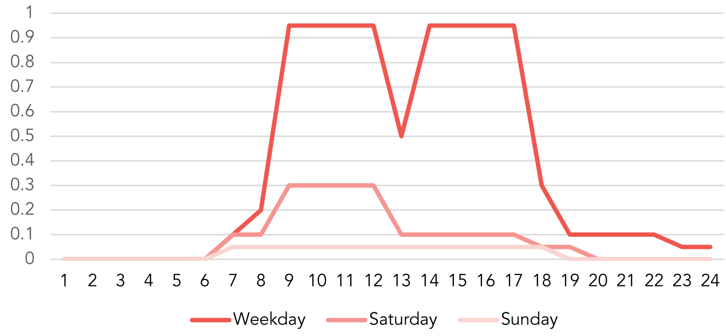
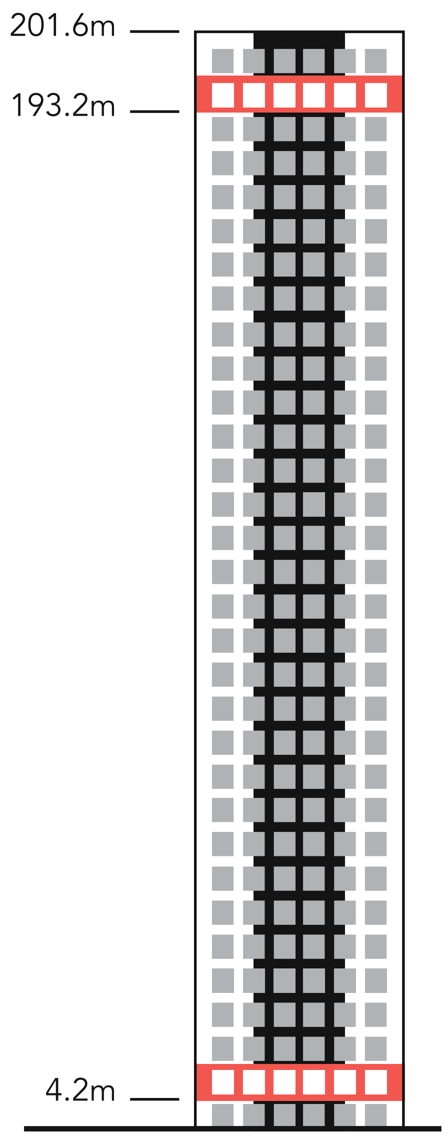


Figure 7.1: Generic office occupancy schedule



Building B
GFA 1800m²

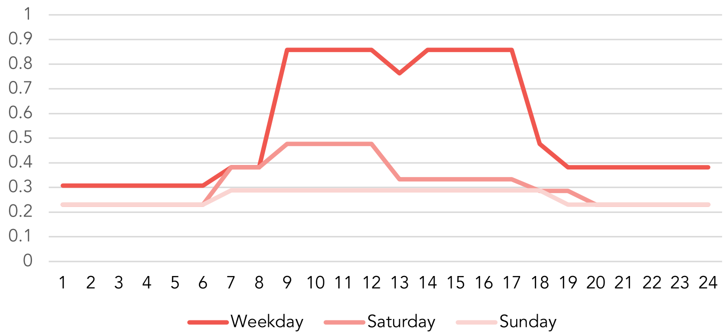


Figure 7.2: Generic office equipment schedule

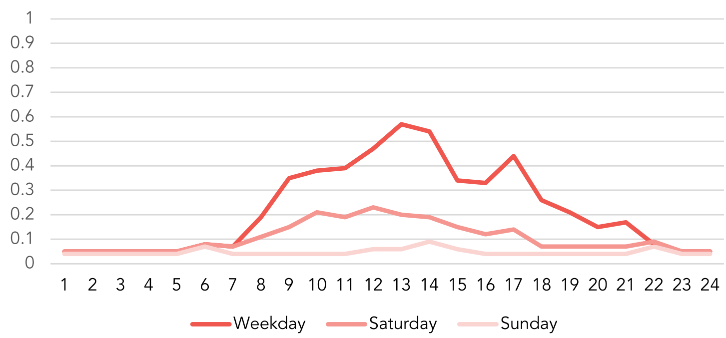


Figure 7.3: Generic office water usage schedule

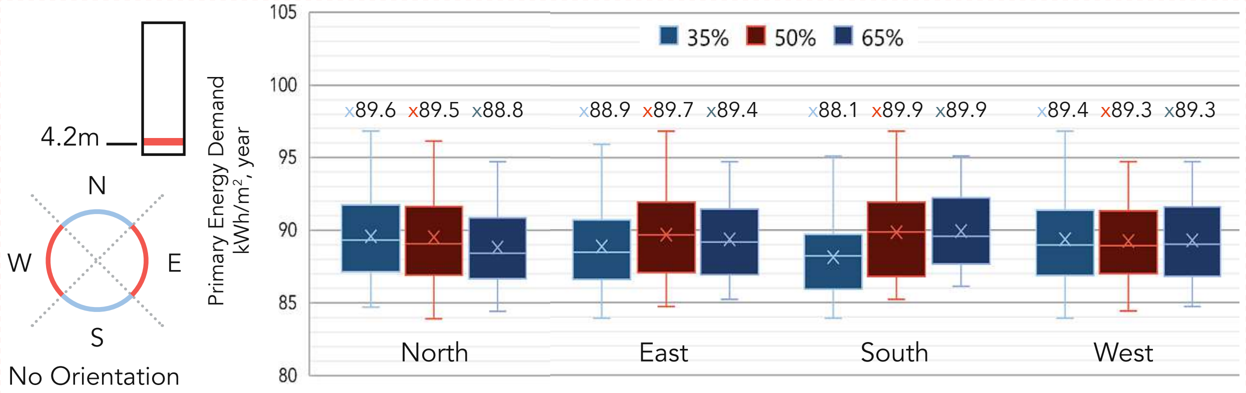


Figure 7.4: Primary Energy Demand for Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a round shape

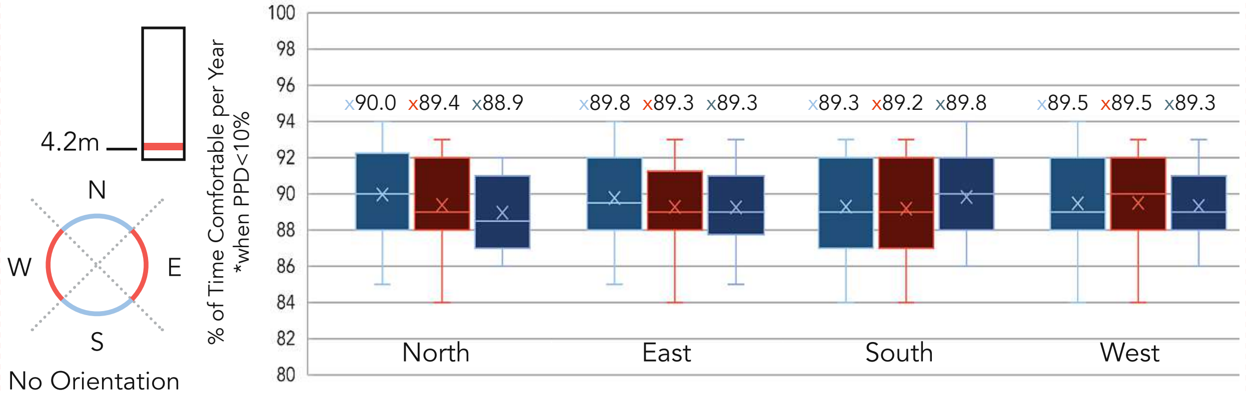


Figure 7.5: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a round shape

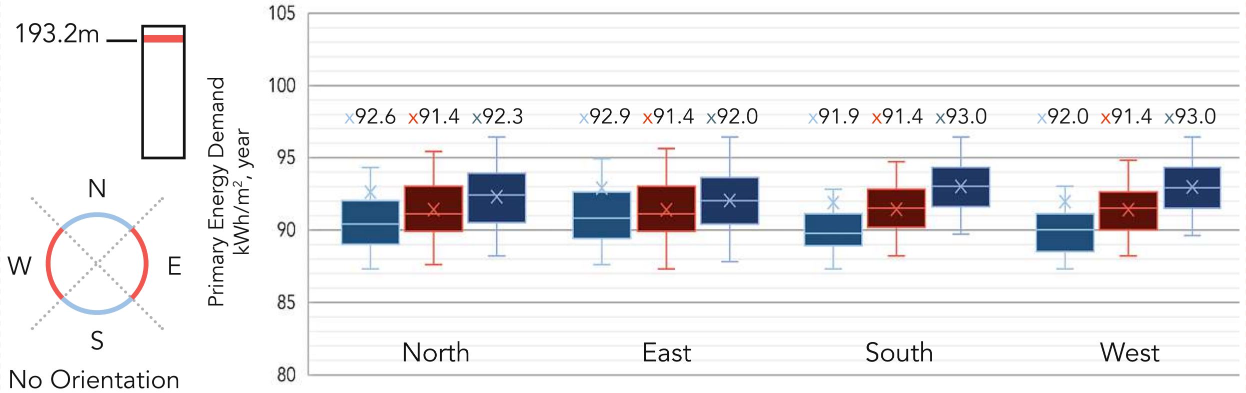


Figure 7.6: Primary Energy Demand for Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a round shape

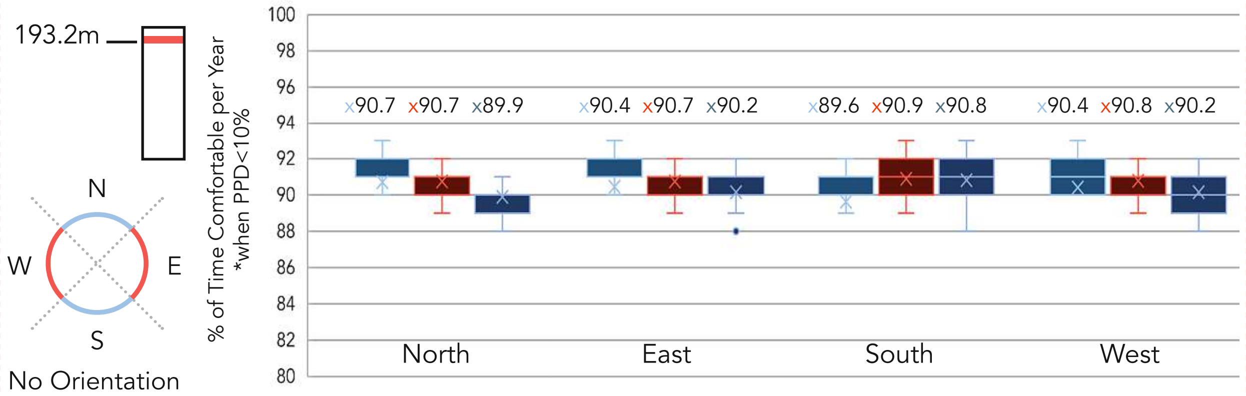


Figure 7.7: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a round shape

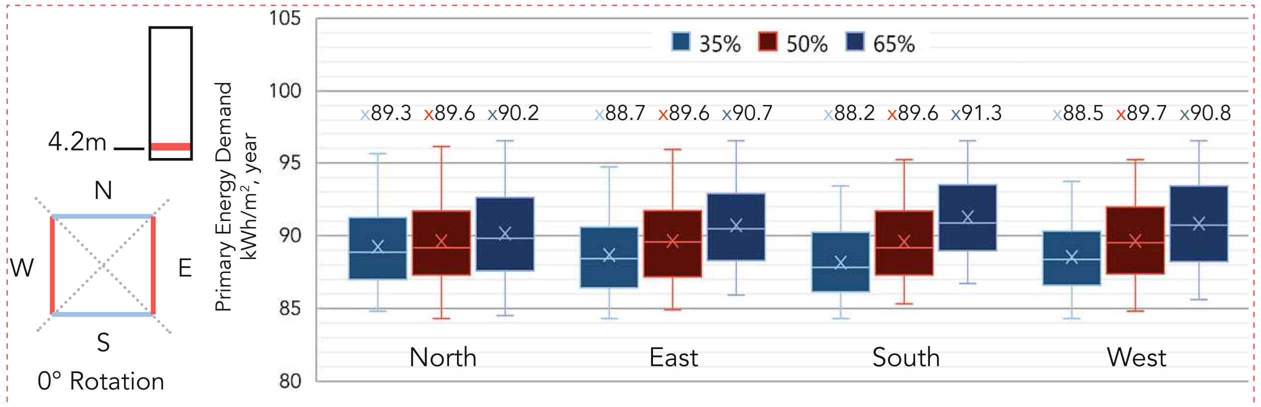


Figure 7.8: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a square shape, rotated 0°

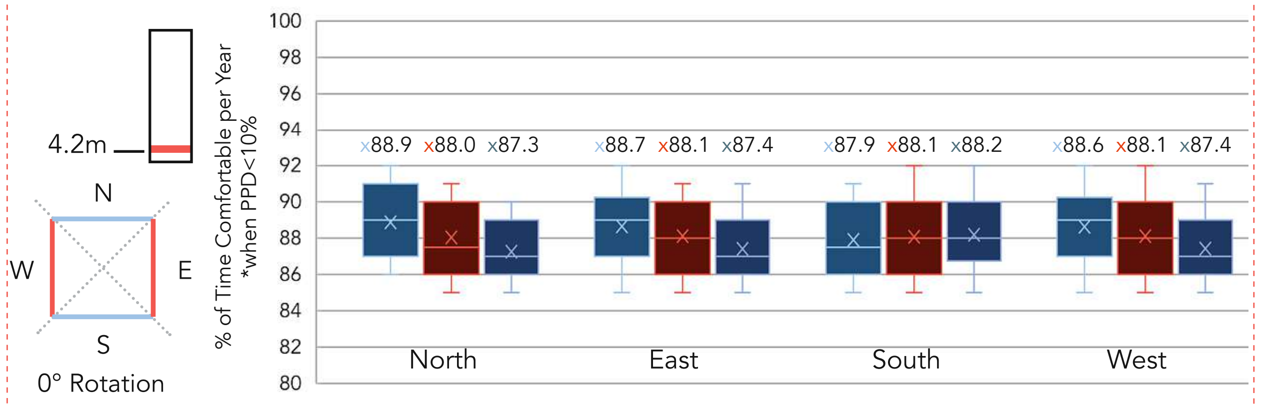


Figure 7.9: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a square shape, rotated 0°

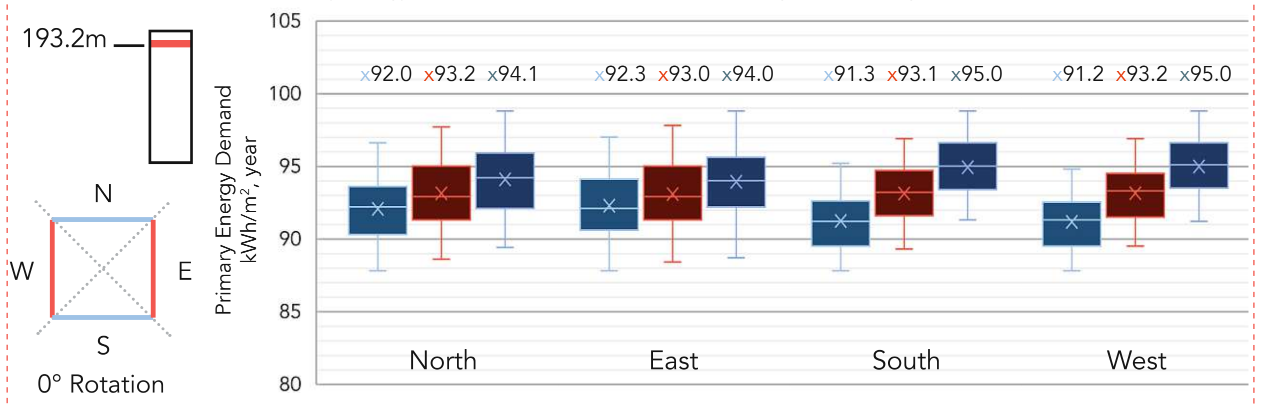


Figure 7.10: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a square shape, rotated 0°

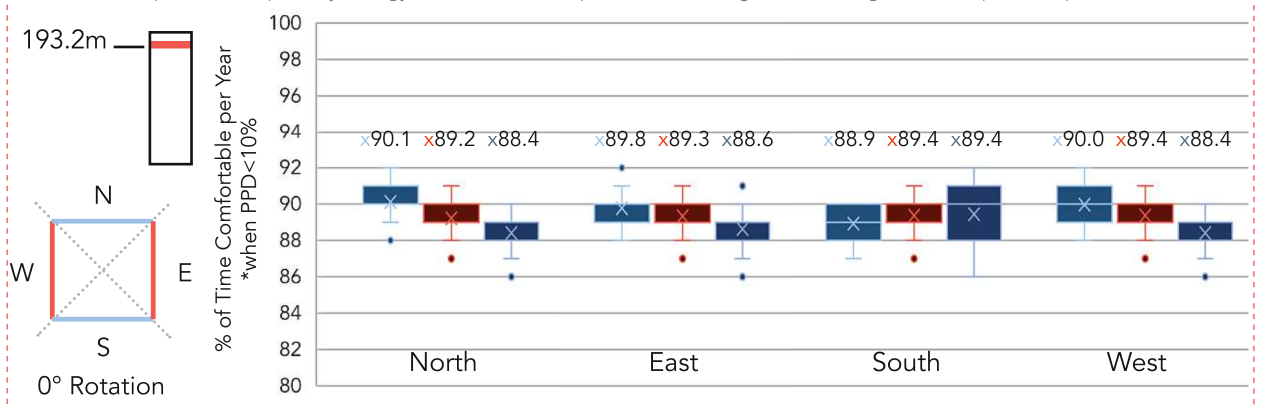


Figure 7.11: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a square shape, rotated 0°

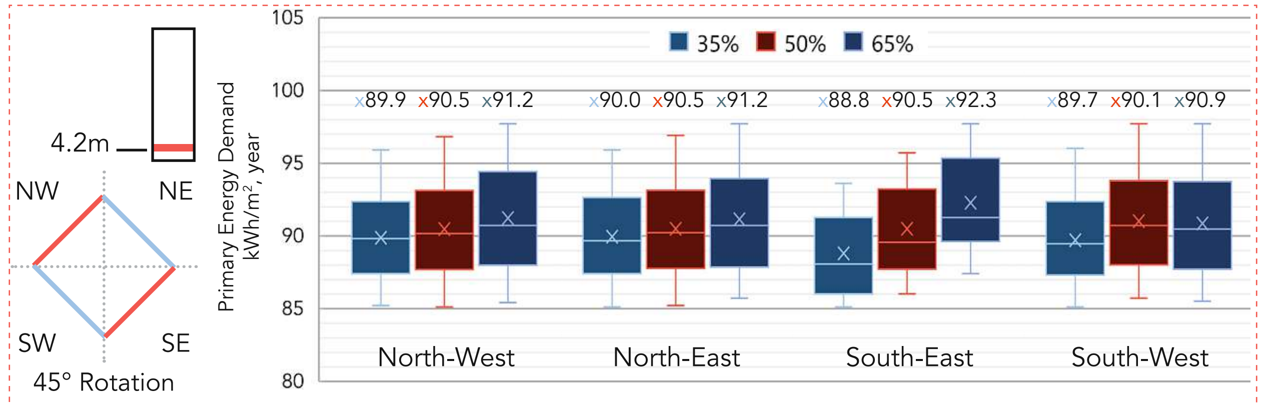


Figure 7.12: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a square shape, rotated 45°

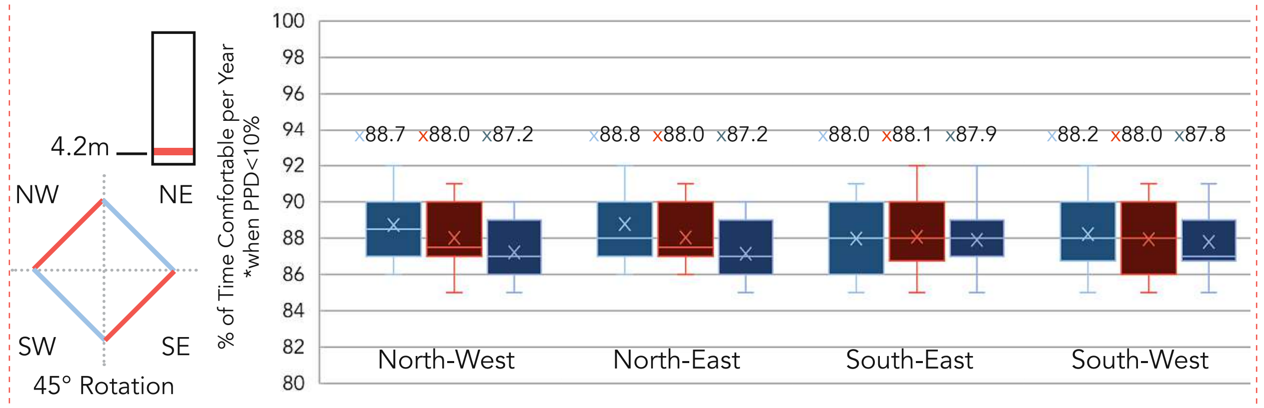


Figure 7.13: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a square shape, rotated 45°

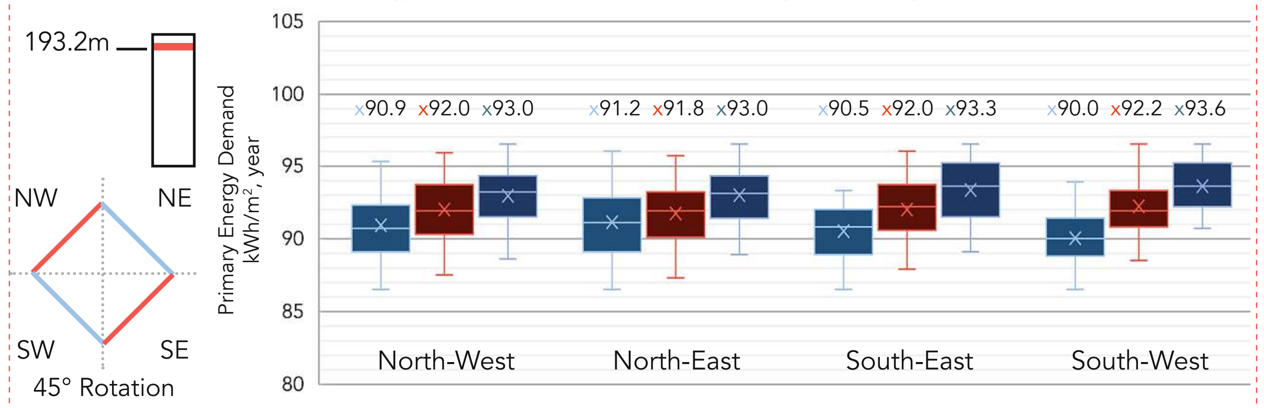


Figure 7.14: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a square shape, rotated 45°

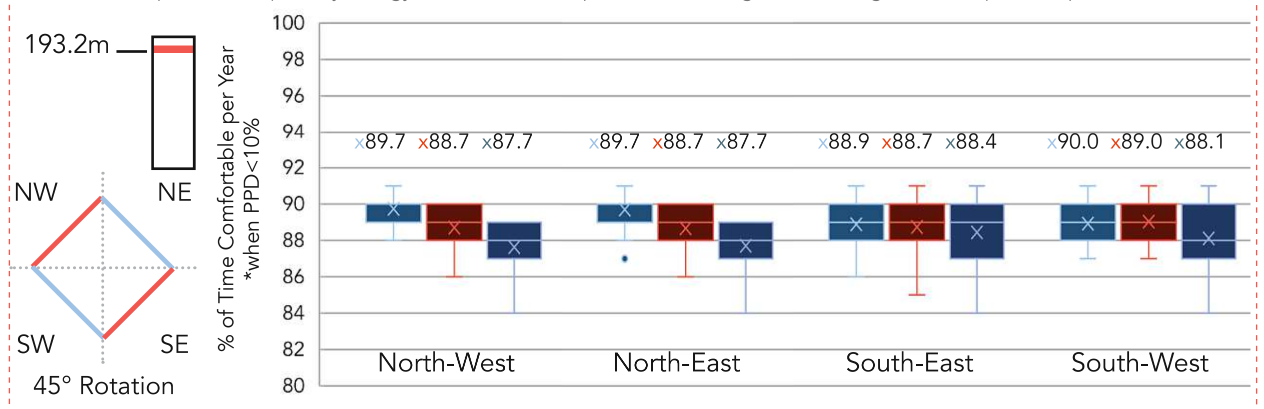


Figure 7.15: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a square shape, rotated 45°

Appendix

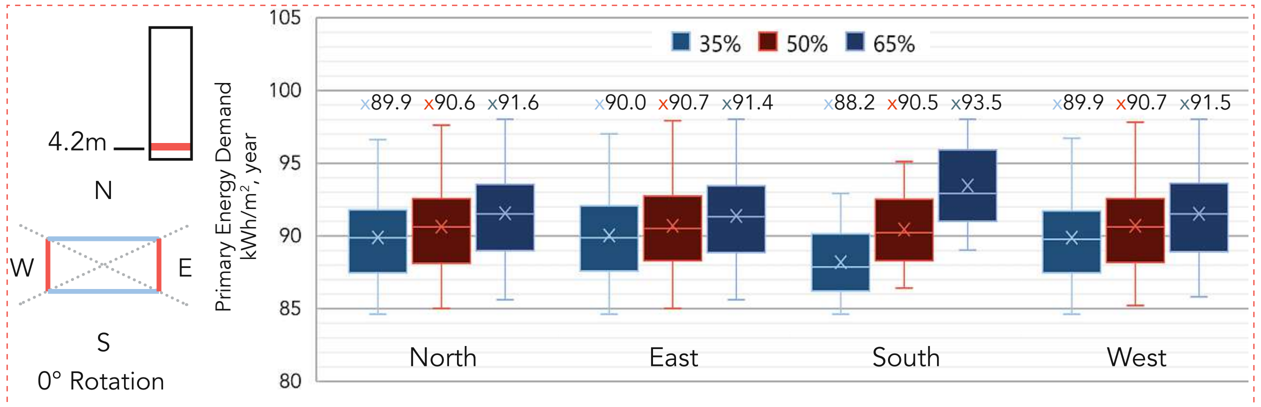


Figure 7.16 Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 0°

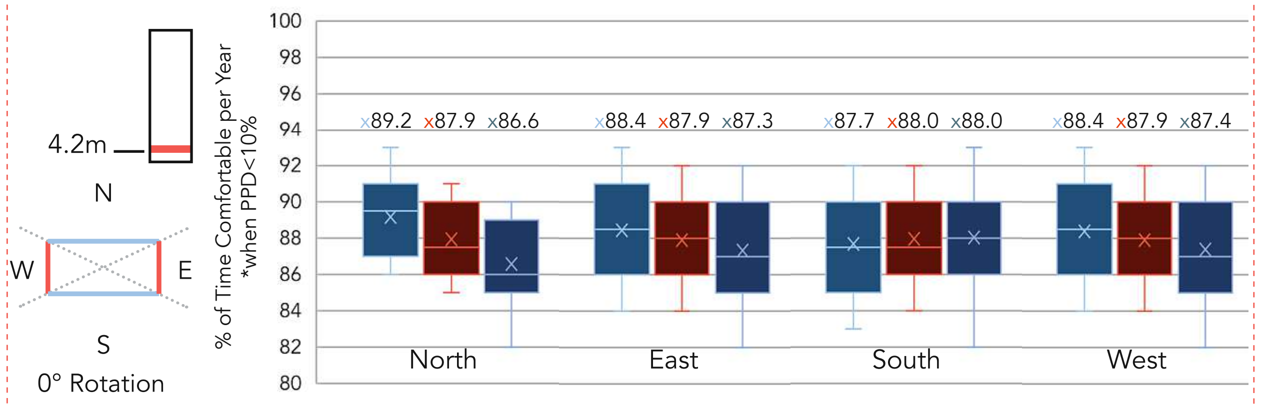


Figure 7.17: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 0°

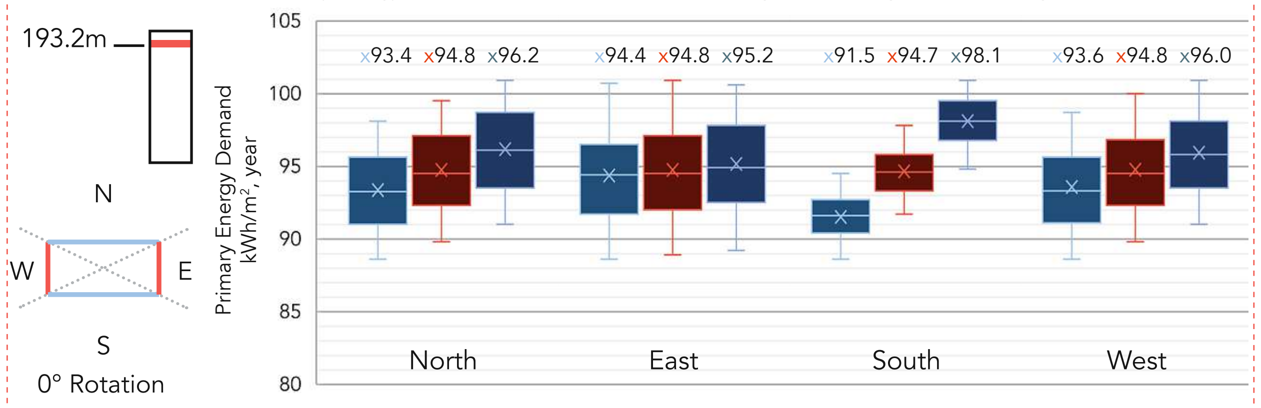


Figure 7.18: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated 0°

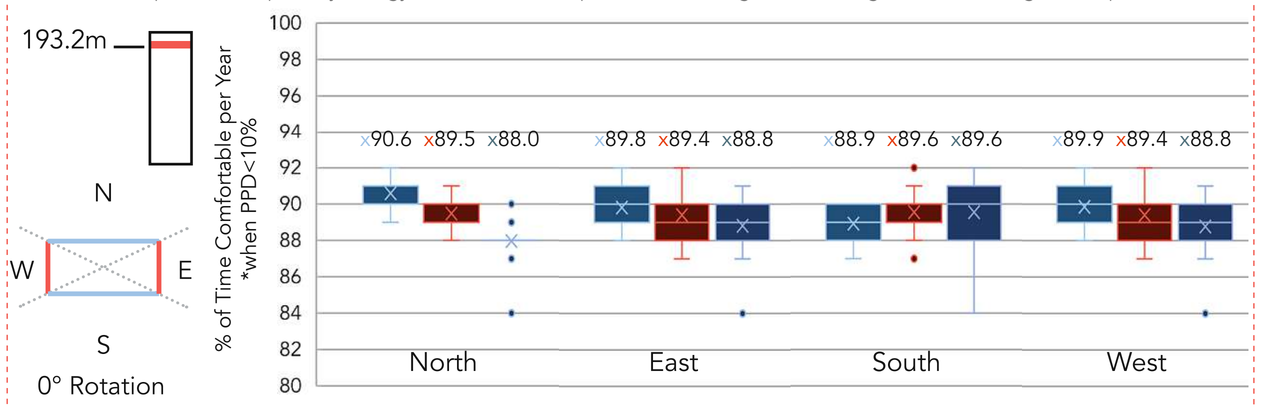


Figure 7.19: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
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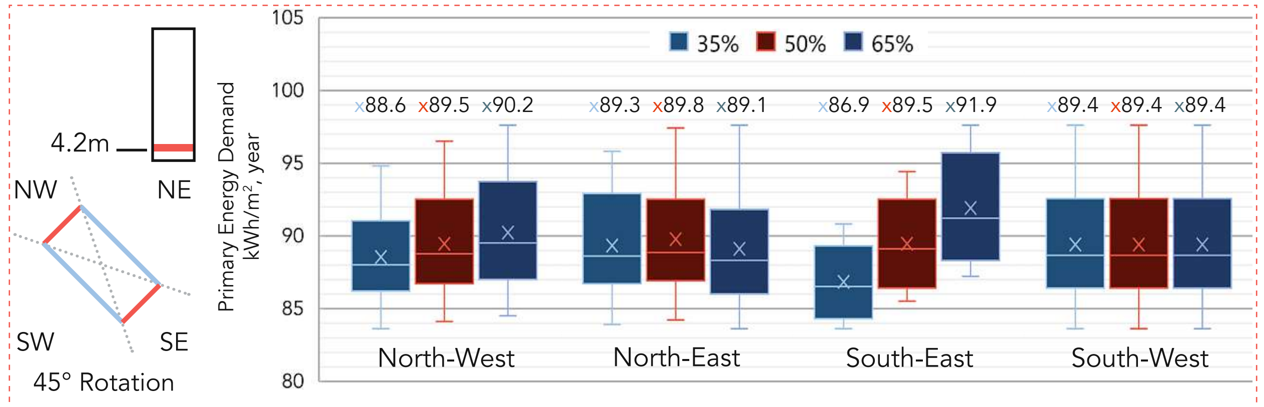

Figure 7.20: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 45°

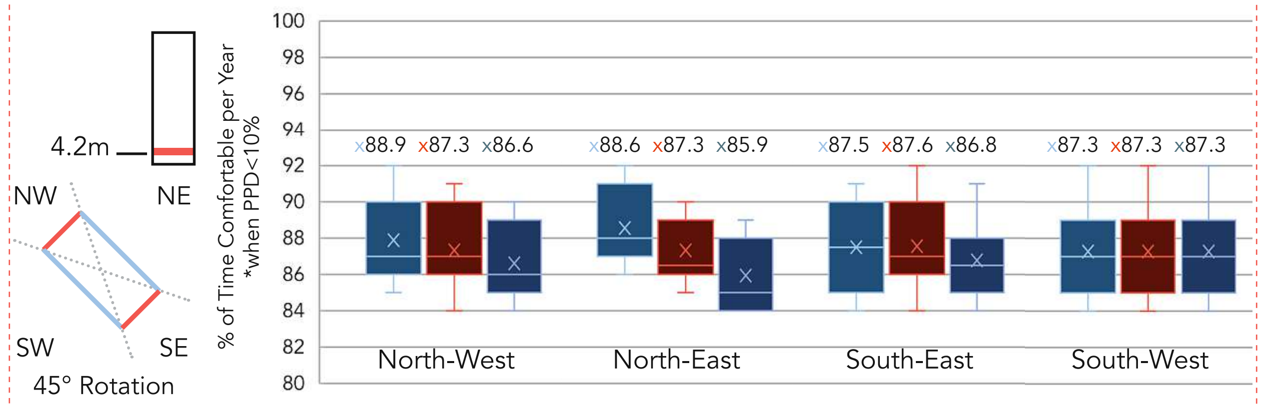

Figure 7.21: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 45°

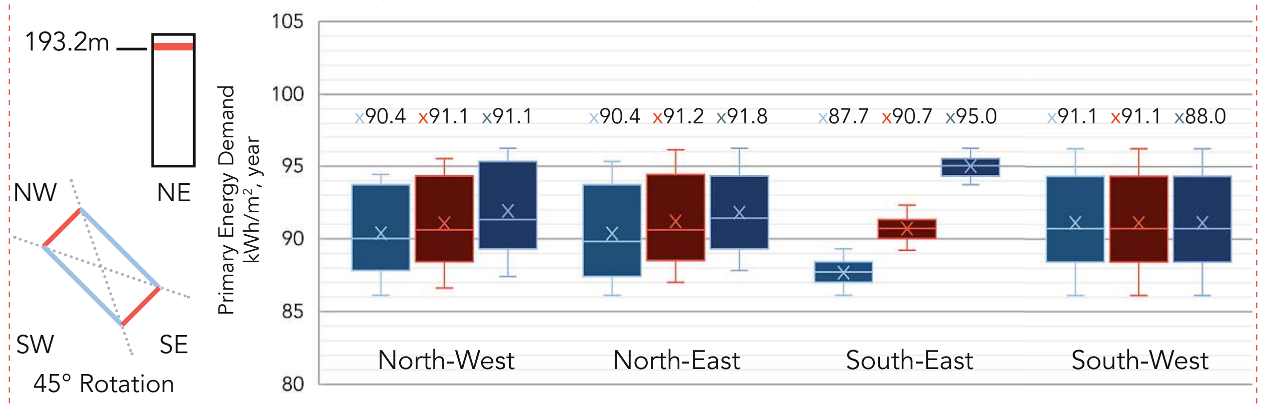

Figure 7.22: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated 45°

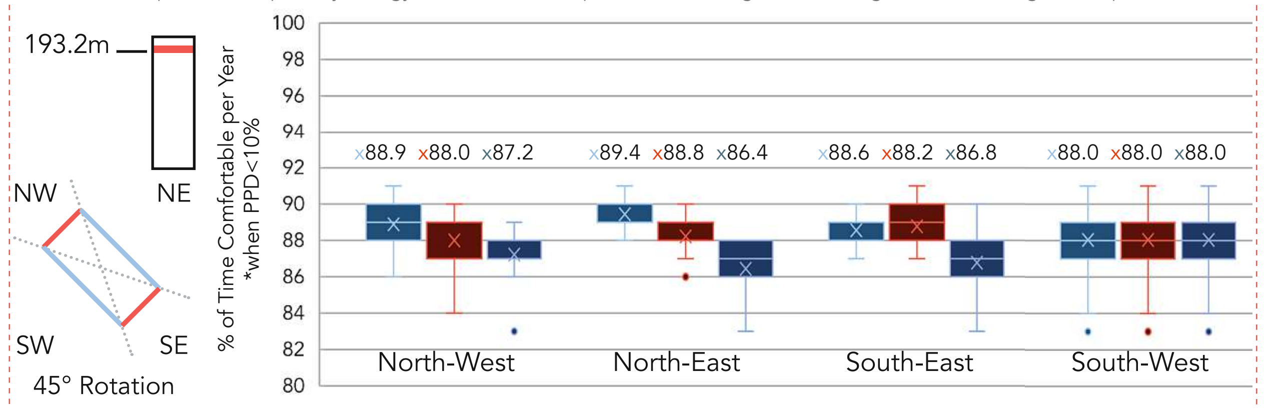

Figure 7.23: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated 45°

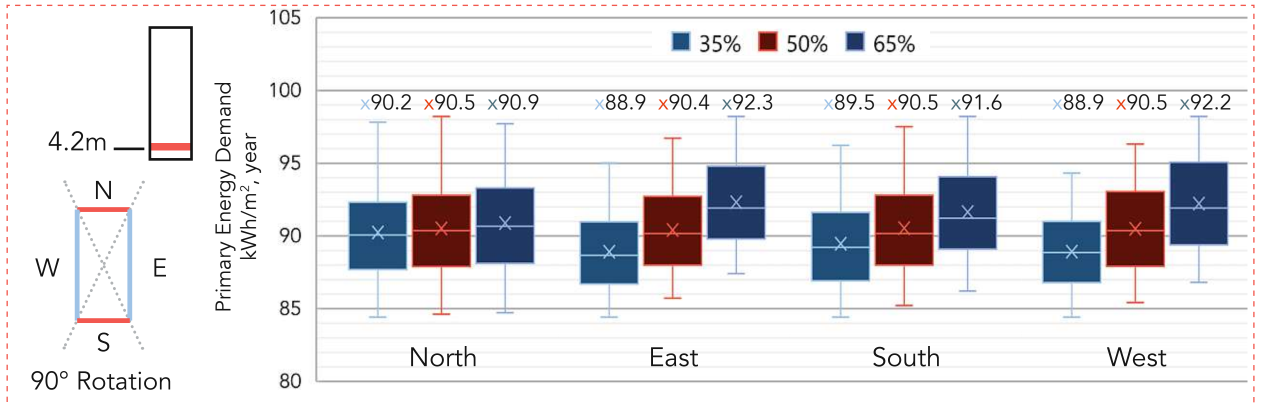

Figure 7.24: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 90°

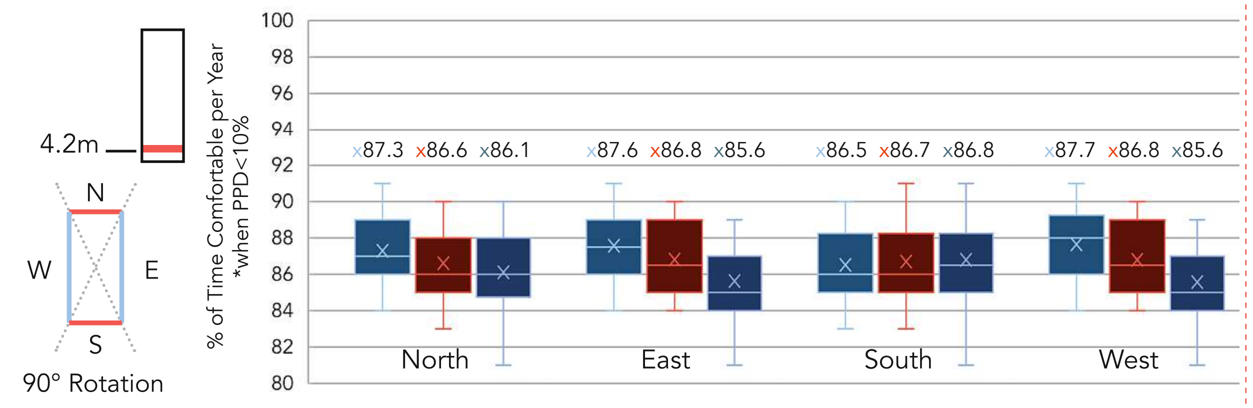

Figure 7.25: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated 90°

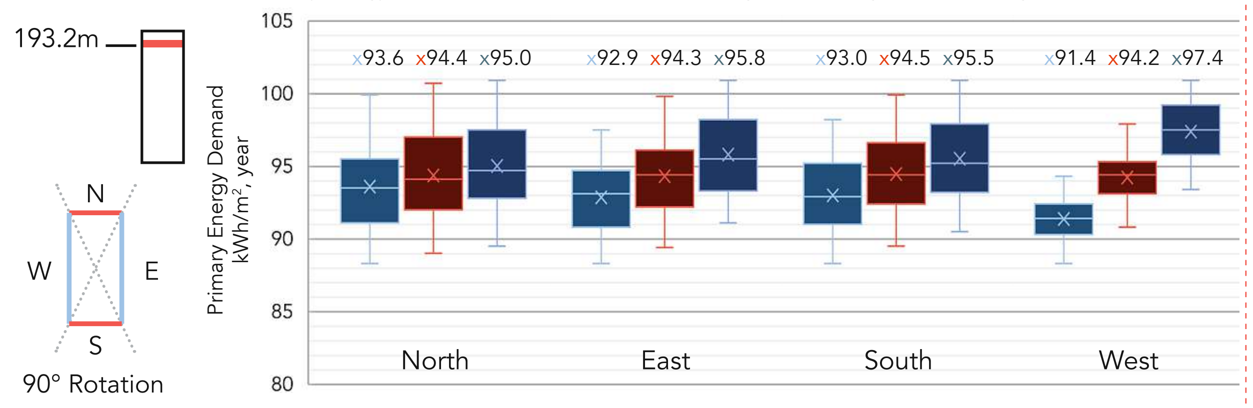

Figure 7.26: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated 90°

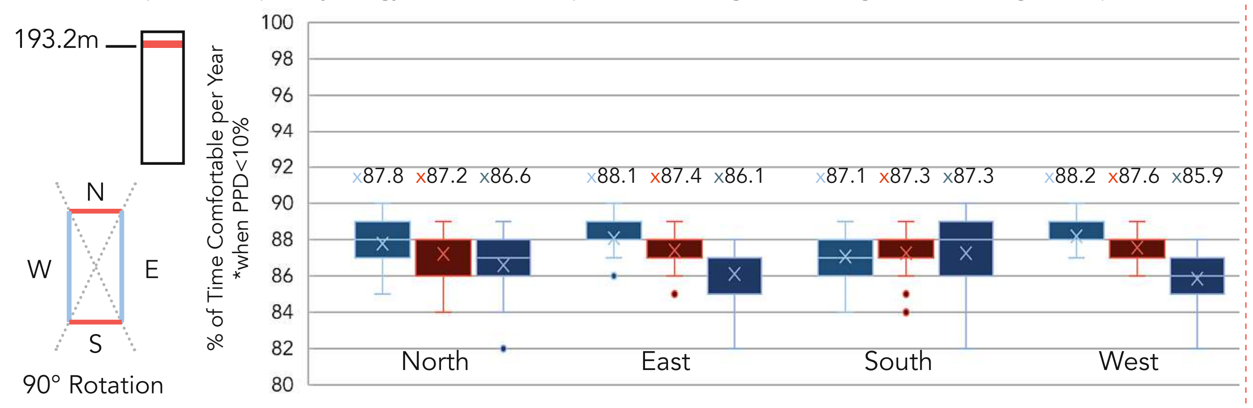

Figure 7.27: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated 90°

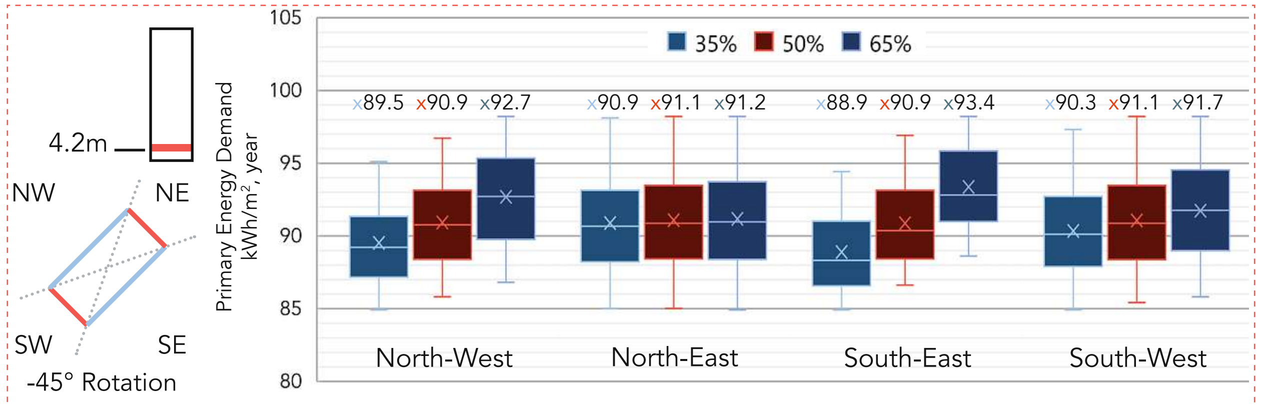

Figure 7.28: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated -45°

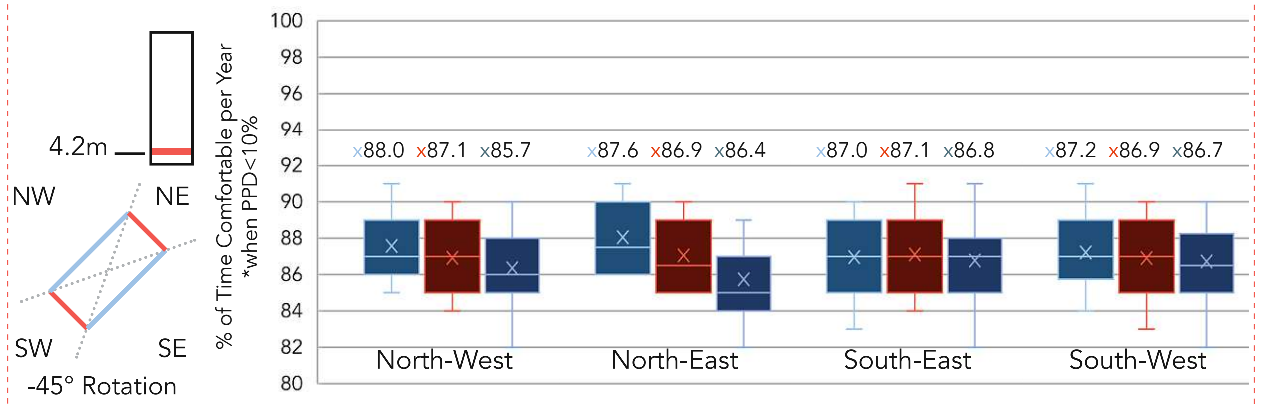

Figure 7.29: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a rectangular shape, rotated -45°

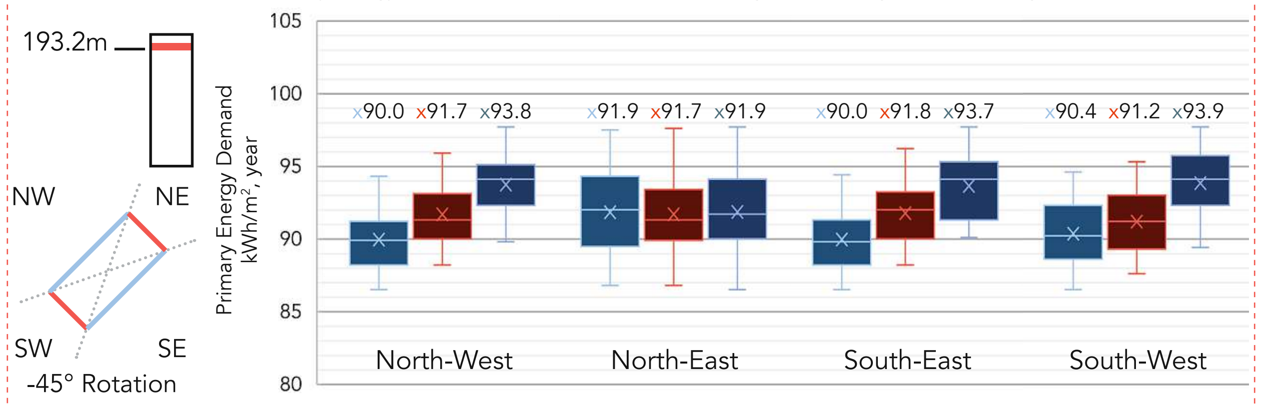

Figure 7.30: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated -45°

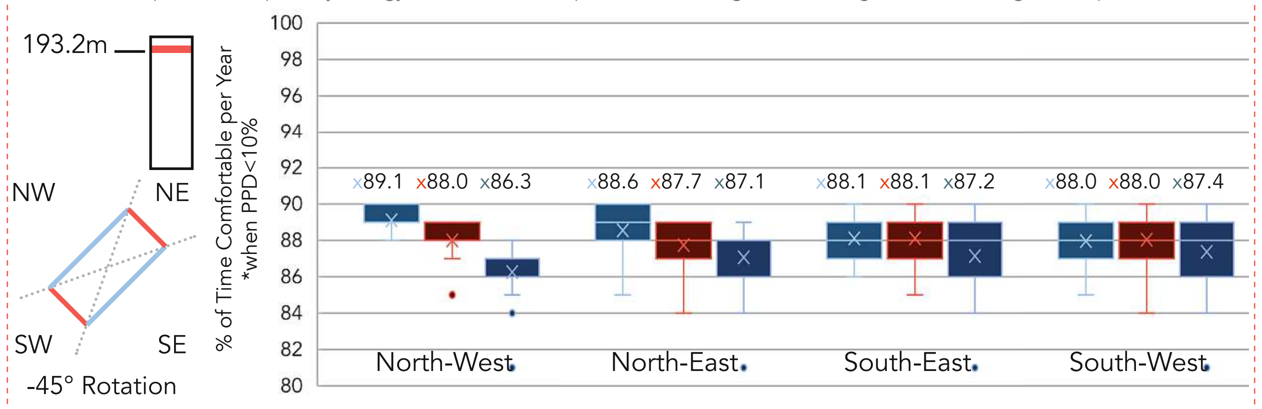

Figure 7.31: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a rectangular shape, rotated -45°

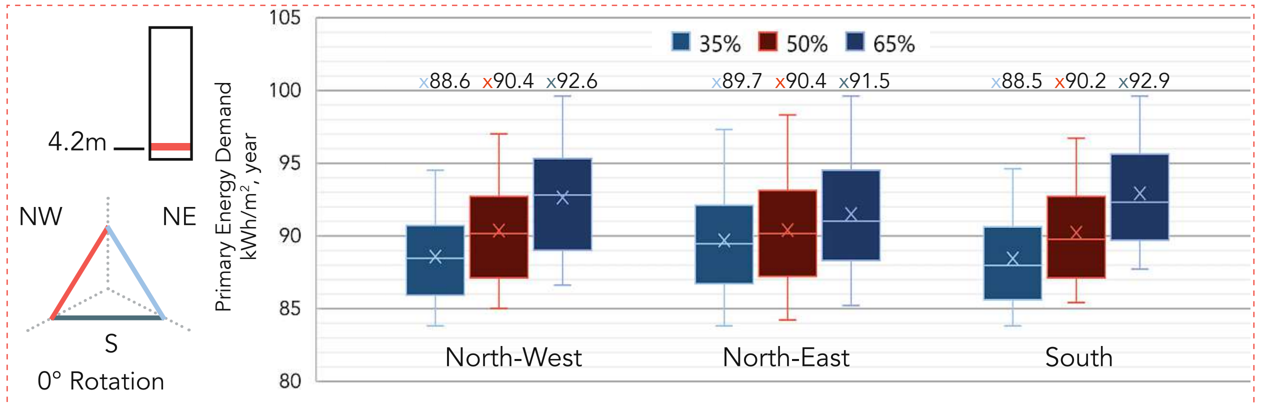

Figure 7.32: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

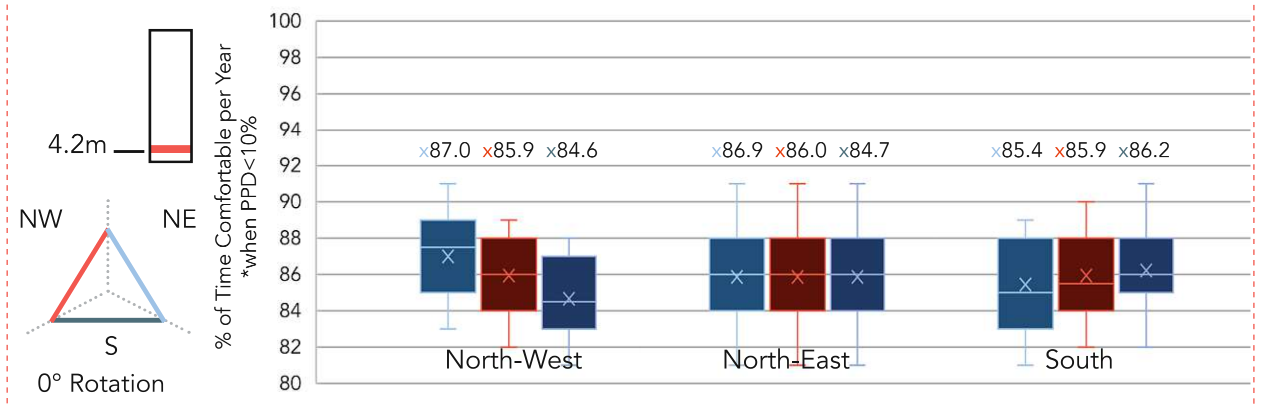

Figure 7.33: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

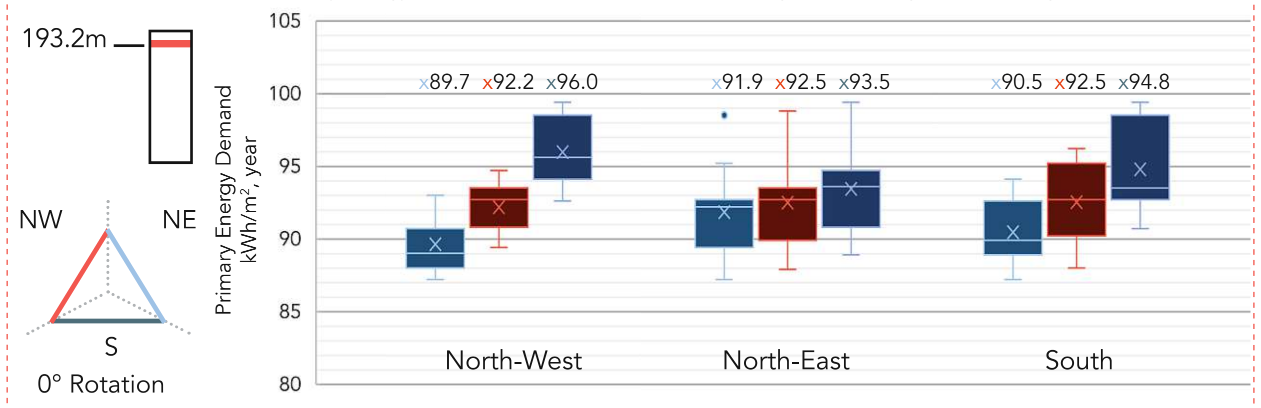

Figure 7.34: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 0°

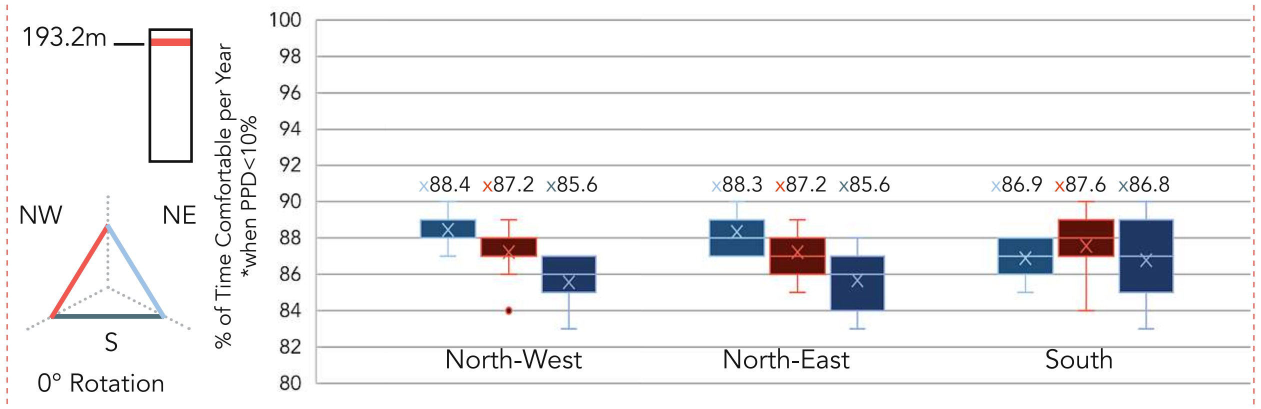

Figure 7.35: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 0°

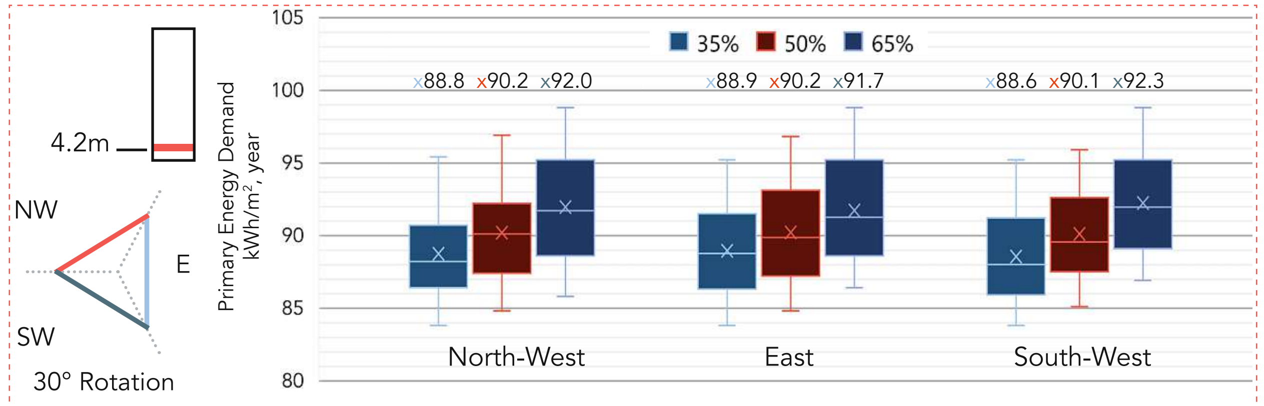

Figure 7.36: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

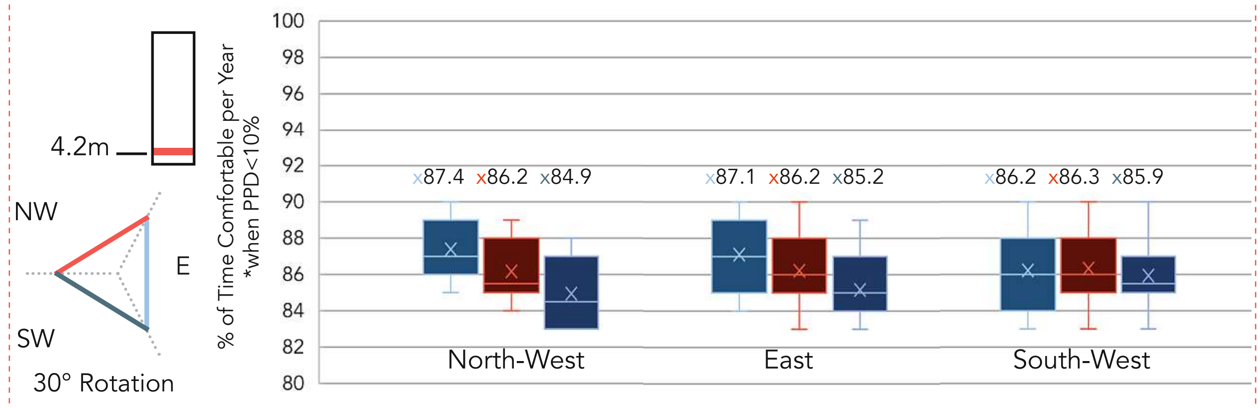

Figure 7.37: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

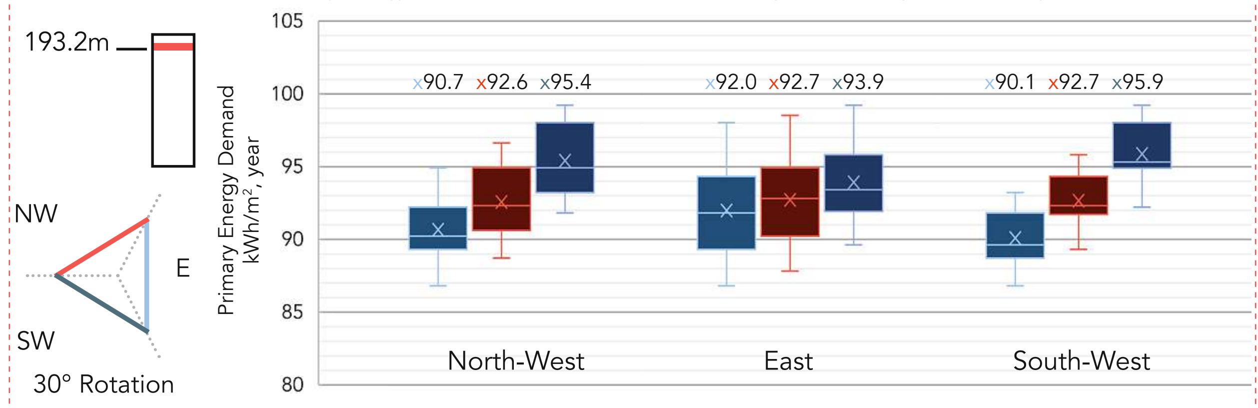

Figure 7.38: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 30°

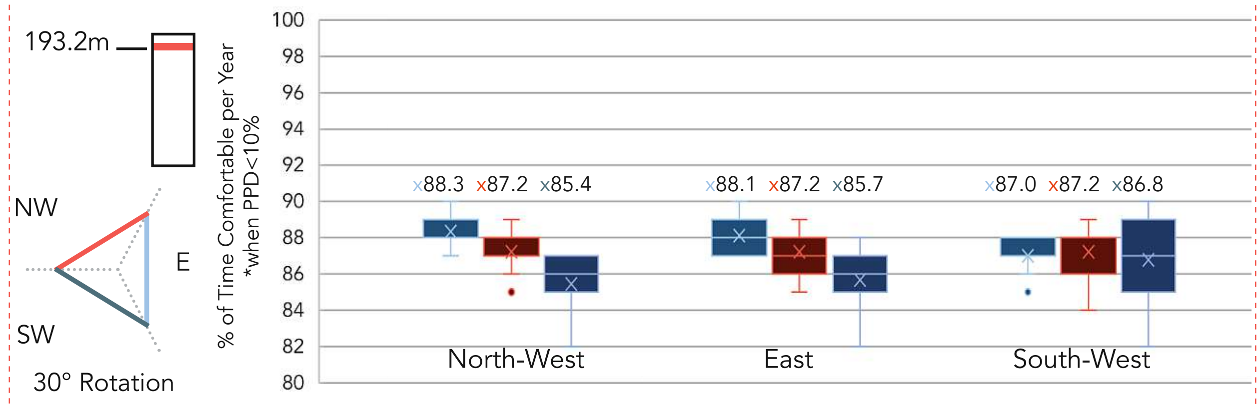

Figure 7.39: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 30°

Appendix

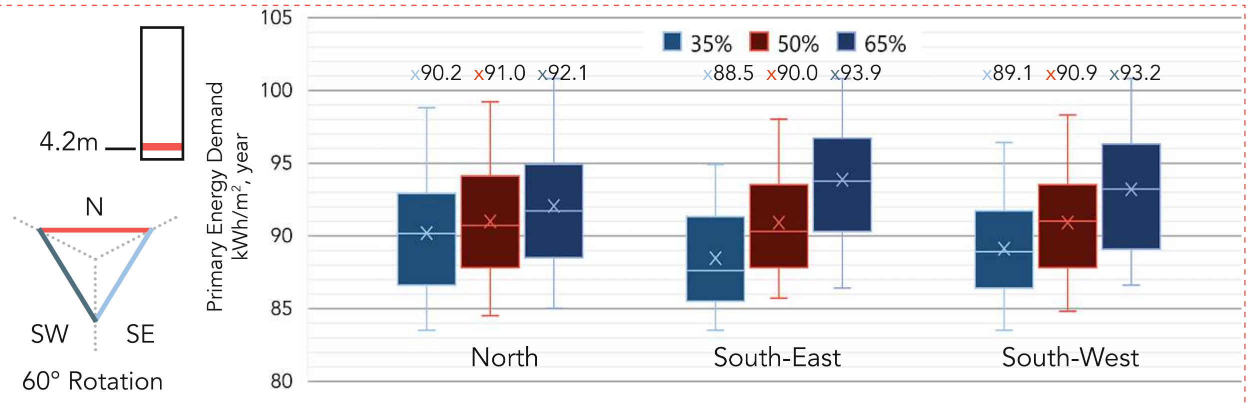

Figure 7.40: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

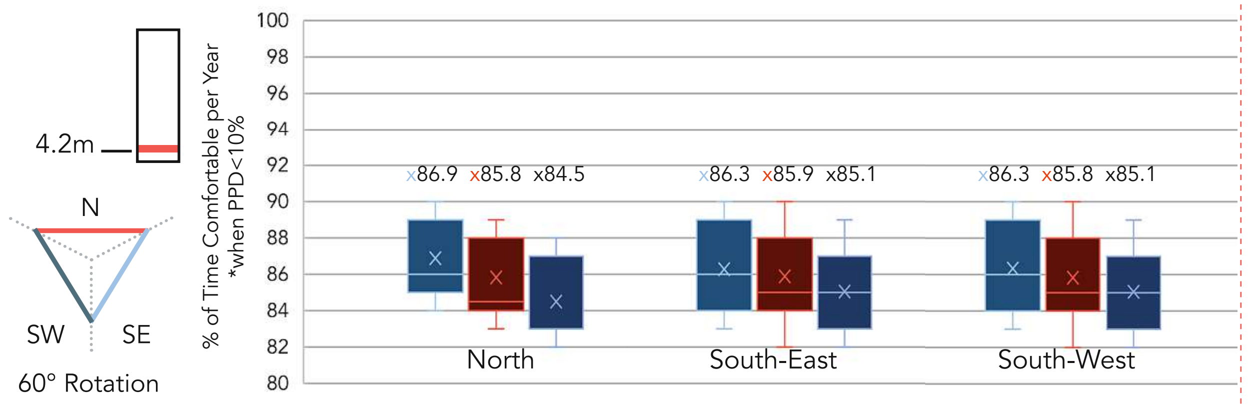

Figure 7.41: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

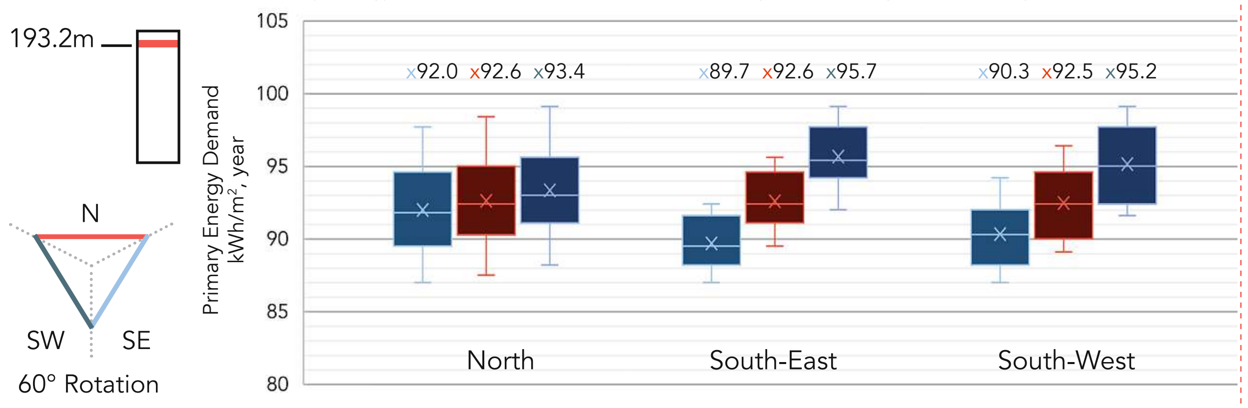

Figure 7.42: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 60°

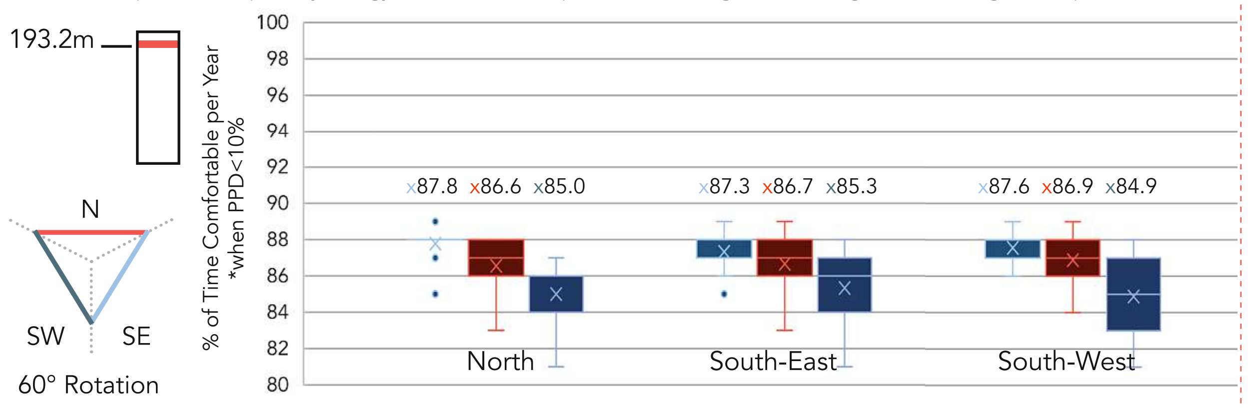

Figure 7.43: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 60°

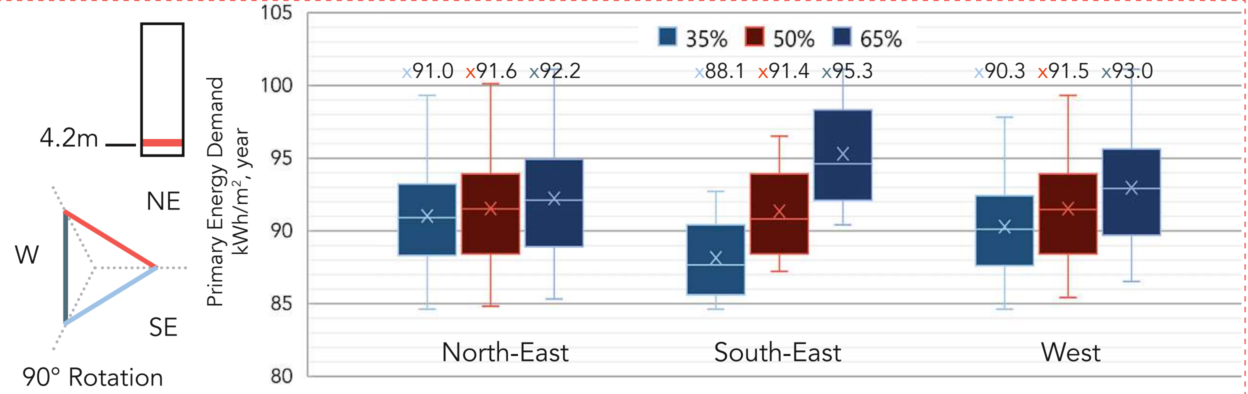

Figure 7.44: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

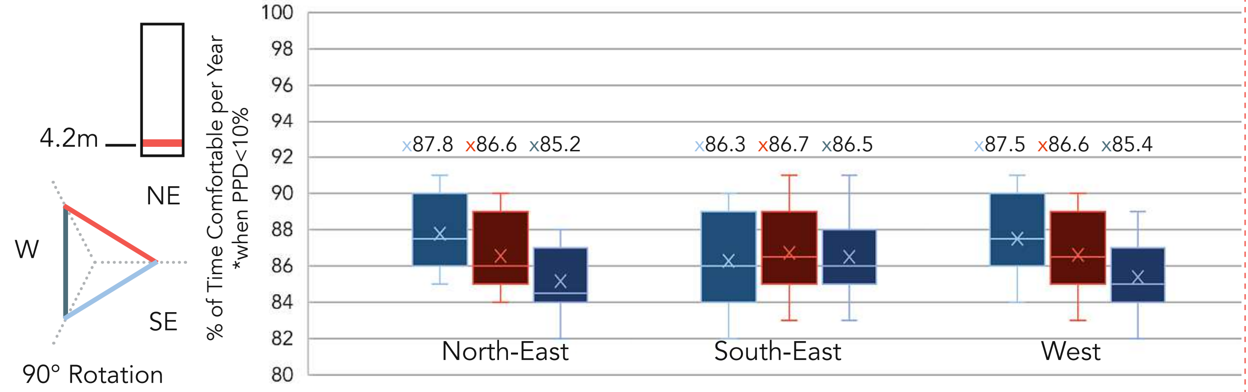

Figure 7.45: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the bottom level of Building B (200m height), for a triangular shape, rotated

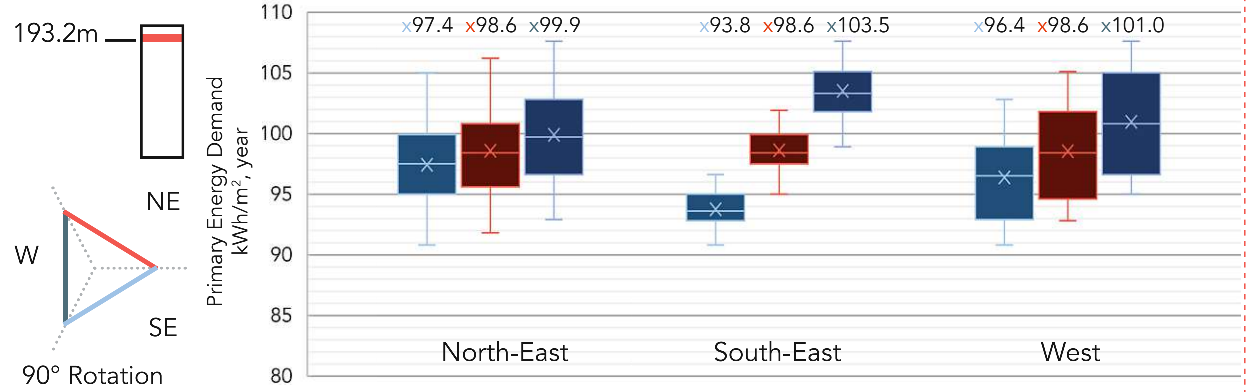

Figure 7.46: Primary Energy Demand with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 90°

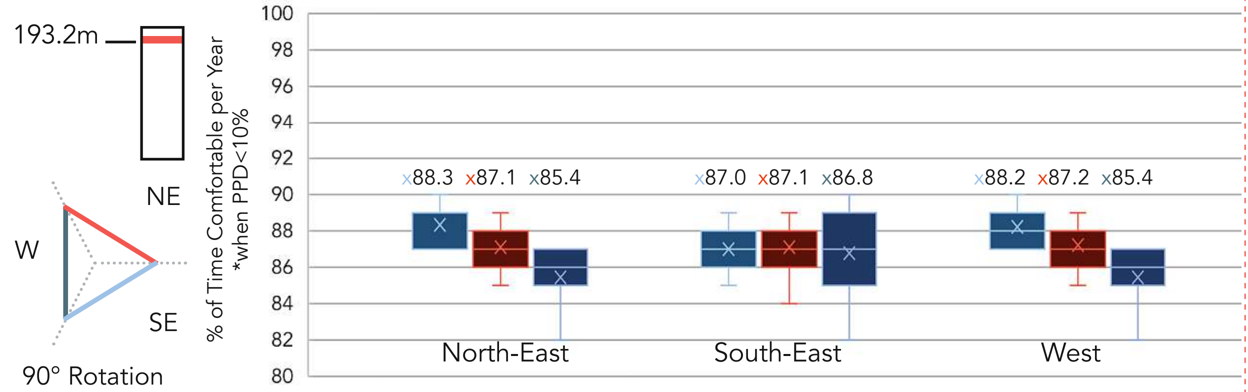

Figure 7.47: % of Time Comfortable per Year with Different Window-to-Wall Ratios on the North, East, South and West Facades
*the results represent the primary energy demand at the top level of Building B (200m height), for a triangular shape, rotated 90°

8

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