#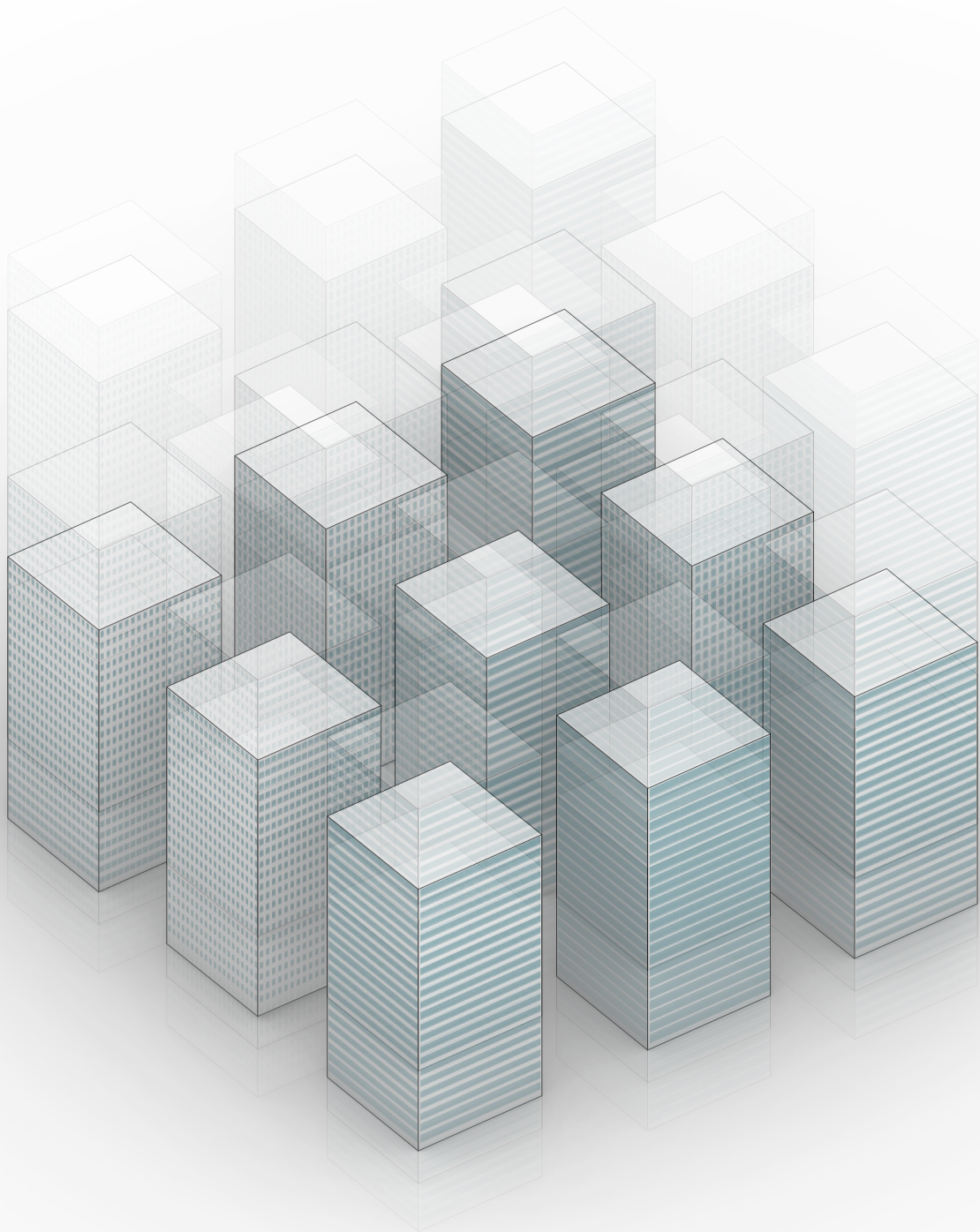 COMPUTATIONAL OPTIMIZATION FOR THE FACADE DESIGN OF A NEARLY ZERO-ENERGY HIGH – RISE OFFICE BUILDING IN THE TEMPERATE CLIMATE

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Master Thesis
Delft University of Technology

COMPUTATIONAL OPTIMIZATION FOR THE FACADE DESIGN OF A NEARLY ZERO-ENERGY HIGH – RISE OFFICE BUILDING IN THE TEMPERATE CLIMATE

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" This is sustainability:

the revolution in our minds

*and in our tools. "*

Françoise Hélène Jourda

Contents

01
Introduction

1.1. Background

Energy performance of the building sector

Buildings are the largest energy consuming sector in the world; they represent more than one-third of the global final energy consumption and an equally important amount of direct and indirect carbon dioxide (CO_2) emissions (International Energy Agency, 2013). In particular, the global buildings sector and the construction industry (manufacturing of materials for buildings) accounted for almost 30% and 6% respectively of the total final energy consumption in 2015. Considering upstream power generation, buildings and the construction sector consumed 28% and 11% respectively of the energy-related CO_2 emissions worldwide (Fig.1.1 and Fig.1.2) (International Energy Agency, 2017).

Global final energy consumption by sector, 2015
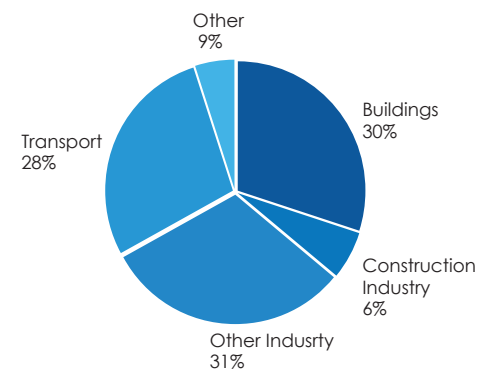
Global energy-related CO_2 emissions by sector, 2015
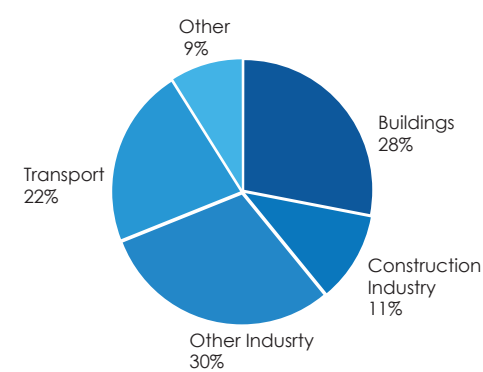
Total energy use per building type for non-residentail buildings in Europe
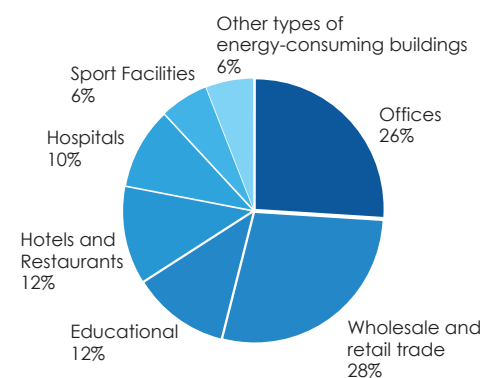

Figure 1.1 (up left): Global final energy consumption by sector, 2015 (International Energy Agency, 2017)

Figure 1.2 (up right): Global energy-related CO_2 emissions by sector, 2015 (International Energy Agency, 2017)

Figure 1.3 (below): Total energy use per building type for non-residentail buildings, for different countries across Europe (BPIE, 2011).

Final energy use in non-residential buildings

According to the survey of the Buildings Performance Institute Europe (BPIE) (2011), considering the European building sector, non-residential buildings consume 40% more energy compared to the residential sector, considering all end energy uses. More specifically, offices, wholesale and retail trade buildings account for more than half of the consumed energy among the non-residential buildings (Fig.1.3). In that sector, the use of electricity increased greatly, by 74%, between 1990-2010 (BPIE, 2011).

In recent years, electricity consumption for office lighting is one of the highest end-uses in the non-residential sector. In 2007, lighting in offices in Europe accounted for 164 TWh. Replacing incandescent lamps with more efficient types, such as LED, has been affirmed to have great potential for energy-saving in lighting end-use, an expected amount of 38TWh by 2010 (BPIE, 2011).

Urbanization and high-rises

Based on United Nations' forecasts, 55% of the world's population lived in urban areas in 2018, a proportion that is expected to rise to 68% by 2050. Therefore, the challenge for meeting the needs of the fast growing urban population will be posed to many countries in the coming future (United Nations, 2018).

In recent years, high – rise buildings are drawing attention, as they appear to be a key to sustainable urbanization. Dr. Anthony Wood (2017) compares quantitatively the sustainability of people's lifestyles between high-rise urban and low-rise suburban case studies. The study shows that urban densification is more effective, as it requires considerably less (a seventh) urban infrastructure provision, compared to the suburban scenario. The latter requires more land usage, and it is related to a higher energy cost and pollution creation, regarding the sectors of infrastructure and mobility (Wood & Du, 2017).
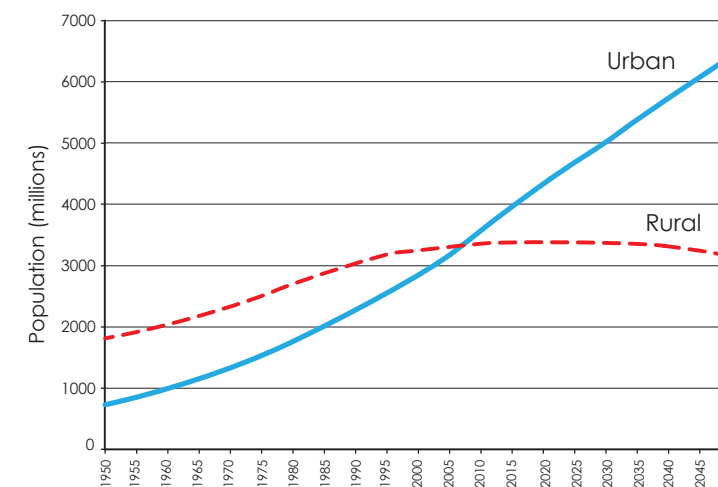

Figure 1.4.: The world's urban and rural populations, 1950-2050 (United Nations, 2015).

Energy consumption of high-rise buildings

Considering end-uses, tall buildings are proven to consume more energy compared to lower ones. Godoy-Shimizu et al. (2018) studied the relation between energy use and height, for office buildings in England and Wales, using the metered consumption of electricity, fossil fuels and carbon emissions annually. The research results show that the mean value of electricity and fossil fuel use is higher by 137% and 42% respectively for buildings with 21 floors and above compared to buildings with five floors and below (Fig. 1.5). The authors suggest that tall buildings consume more energy because of the specific climatic conditions (higher wind speed, more solar gain and lower temperature) that they are exposed to (Godoy-Shimizu et al., 2018).

Particularities of high-rises

For that reason, special attention should be paid to the particularities of that type of buildings. The energy performance of high – rise buildings depends on different climate parameters that are affected by the building height. For instance, the outdoor air temperature of the top floors of a high – rise building is lower compared to that of the lower floors. Also, the wind speed increases with the building height (Raji, 2018). These phenomena could dictate different design decisions, for example, different w/w ratio in the façade, insulating materials or shading strategy. What is more, the urban context seems to have a greater effect in that form of buildings, compared to low-rise constructions. For example, the lower floors of a high-rise may be shaded by nearby – buildings, meaning that no shading would be required, in contrast to upper floors, which are usually exposed to solar radiation for most of the time in the year. Last but not least, different design for each facade is required based on the orientation, regarding, for example, exposure to sun or prevailing winds.
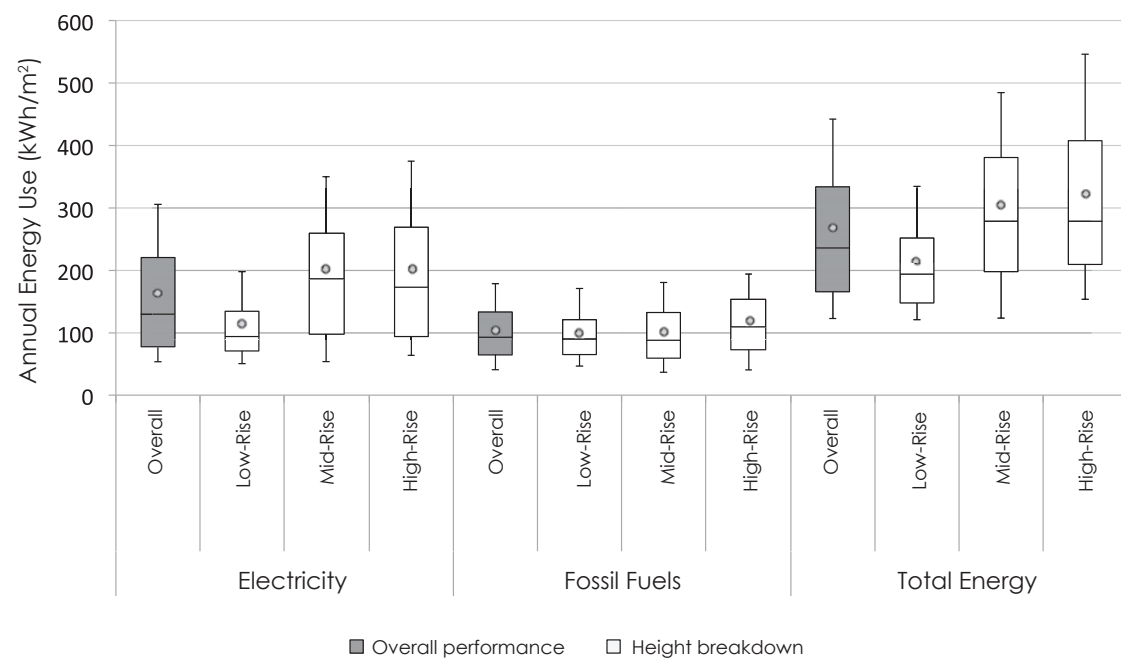
Figure 1.5: Comparison between offices according to building height, regarding electricity, fossil fuel and total energy use (Godoy-Shimizu et al., 2018).

High-rise building definition

Within literature, different definitions for high rises have been found, and most of them take into account the building height or the number of stories. According to the Council of Tall Buildings and Urban Habitats (CTBUH, 2019), a building with 14 or more floors, or higher than 50m, and lower than 300m is considered as tall building. It is also noted that a building higher than 300m and lower than 600m is classified as supertall, while a building higher than this threshold is considered as megatall. Following that categorization, that research deals with buildings between 50-300m high, as nowadays that is the most common type of tall buildings: there are only 143 supertall and 3 megatall buildings completed until now worldwide.
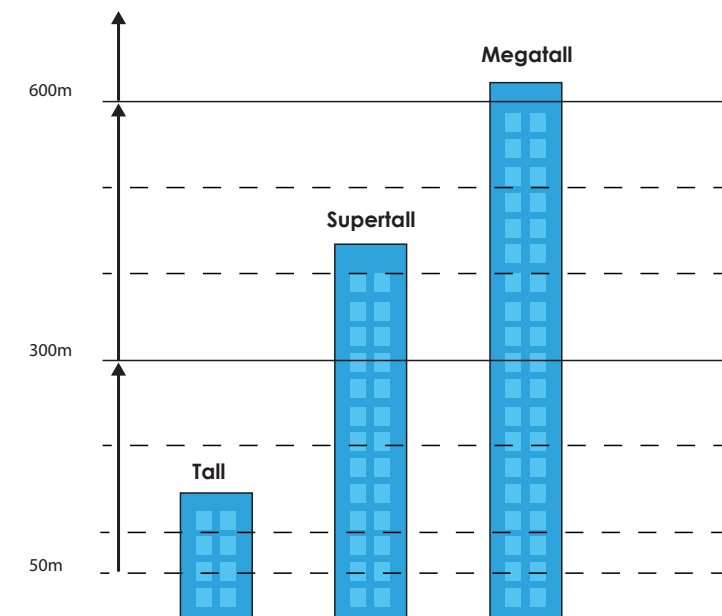
Figure 1.6: Categorization of buildings according to height. Adapted from: (CTBUH, 2019).

Comparison between conventional and integrated design processes

It is proven that decisions made in early design stages have the greatest impact on the overall performance of the building (Shi & Yang, 2013). For that reason, many researchers suggest the integration of systematic approaches in the conceptual design phase, that support designers in decision-making based on measurable criteria. The MacLeamy curve (Fig.1.7) suggests shifting the design effort forward in the project timeline, as the ability to impact the performance and the cost of the design is much greater then compared to later design stages (Daniel Overbey, n.d.).
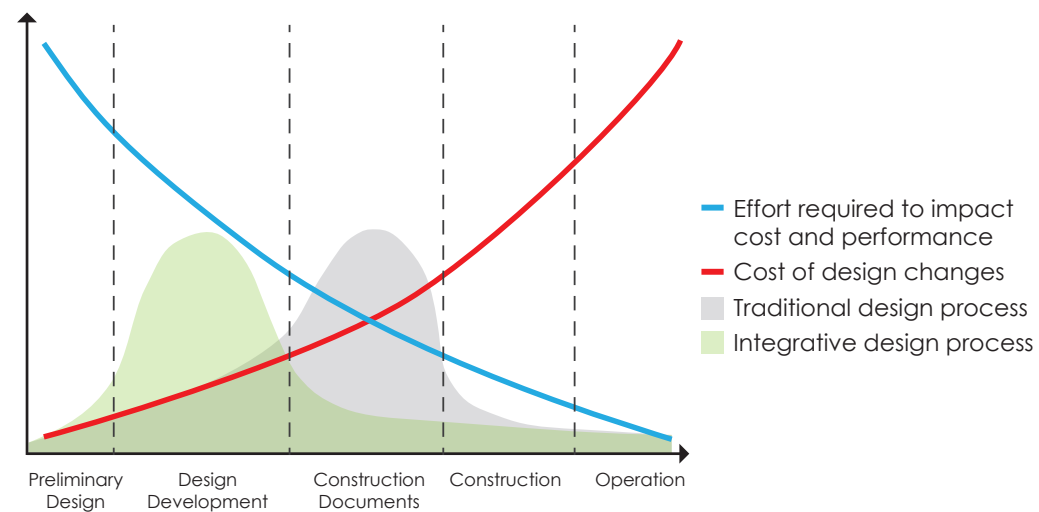
Figure 1.7: The MacLeamy curve. Adapted from:(Daniel Overbey, n.d.).

The concept of performance-based architectural design represents a principle or a methodology that the designer/engineer follows, in order to emphasize different performances of the building (Shi, 2010). In the scope of that study, special attention is given to research and initiatives regarding building energy performance. The concept of performance based design was introduced in the architectural, engineering and construction (AEC) industry in the end of the 20th century, due to the emerging need for sustainable design. According to that conventional approach, that is used by many companies in AEC industry until today, in the conceptual design phase, the architect develops a design and assesses one or more performances of the design instance with the help of energy simulation programmes. After the assessment of the results, the designer modifies the design, aiming for a better performance (Fig.1.8). That iterative design process is intense time-consuming and leads to the evaluation of a limited number of designs. Therefore, the optimal design can barely be achieved (Shi, 2010).

In performance-driven approaches, optimization techniques, with the use of optimization algorithms in most cases, automate the design process (Shi, 2010). Many researchers suggest the use of integrated computational design methodologies that facilitate parametric design environments, simulation

programmes, and also optimization loops (Gerber & Lin, 2014 ; Méndez, Capozzoli, Cascone, & Sassone, 2015 ; Shi & Yang, 2013 ; Turrin, Von Buelow, & Stouffs, 2011 ; Turrin et al., 2011). Optimization processes decrease the time to reach the best performing designs, enable designers explore big solution spaces and extract knowledge from that systematic approach (Fig.1.9).
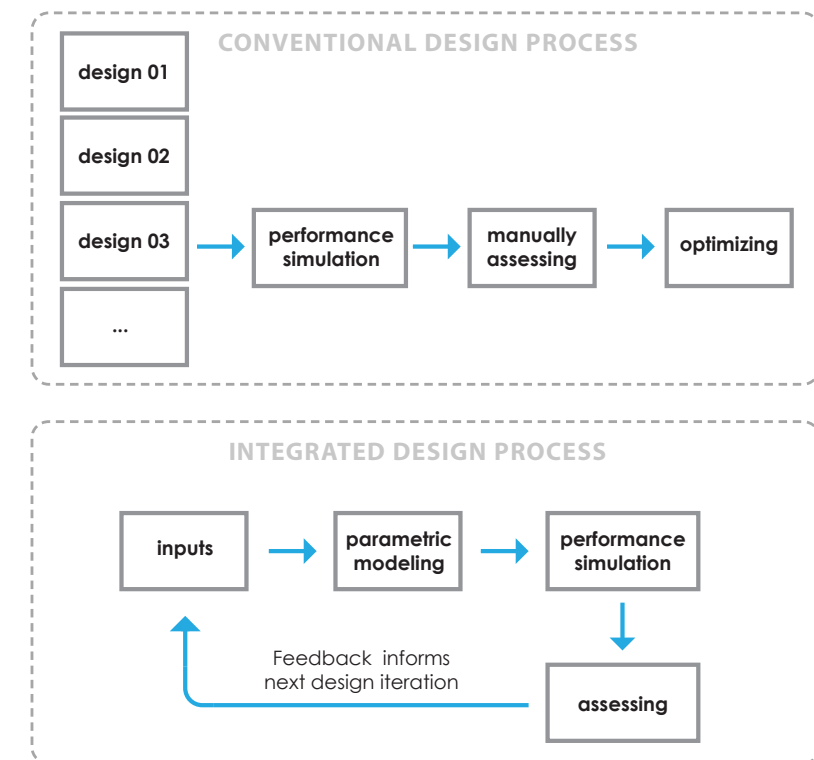
Figure 1.8: Schematic of the conventional approach for performance based design. Adapted from: (Shi, 2010).

Figure 1.9: Schematic of the integrated performance-driven architectural design. Adapted from: (Shi, 2010).

1.2. Problem statement

In the late 1920s and early 1930s, the tall building was already a major architectural typology in US, while in European cities, it became a prominent feature after the Second World War. In the modern city, the tall building was a response and a consequence of economic and industrial change, and technological challenges as well. Until the first half of the 20th century, passive strategies were incorporated in the architectural design of high-rises, regarding size and positioning of the windows and solar protection, as well as shape and depth of the floor plans. In the late 1950s, the design of high-rises, especially the office building, turned to the use of air conditioning and artificial (fluorescent) lighting.

That gave the freedom to architects to introduce new features in the design of tall buildings (curtain wall, open plan configuration), without the need of keeping a direct communication with the external environment. Consequently, the high-rise building resulted in a building model of a poor relationship with the urban context, climate and urban design. However, because of the '70s energy crisis and the environmental awareness in the following two decades, the role of architecture in environmental design acquired an importance on an international scale. In the 1990s, specifically Europe put great emphasis to the subject of energy efficiency in the architectural agenda. New design proposals for high-rise buildings were discussed, in response to the increasing global environmental pressures (Goncalves & Umakoshi, 2010). In that context, a growing number of countries, all over the world, have taken measures in order to improve buildings energy performance, and they have developed regulations for nearly Zero – Energy buildings (nZEB). Europe has introduced the Energy performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (European Commission, 2010), and in USA, the American Society of Heating, Refrigerating and Air-Conditioning Engineers has developed the ASHRAE Vision 2020 (ASHRAE, 2008).

In spite of the technological advances in the construction industry, the awareness for environmental design and the international regulations towards energy efficient buildings, a number of proclaimed environmental tall buildings around the world are false paradigms and have high environmental load. The establishment of an over-glazed high-rise building, with no shading devices, as a global symbol of the commercial tower can no longer be acceptable in the light of nZEBs. Conventional tall buildings are proved to consume more energy per square meter than low-rise buildings (Lam et al., 2004). The poor performance in that kind of buildings is related to high energy consumption (cooling, heating, lighting and ventilation) and poor thermal comfort.

The problem that is posed is the lack of knowledge and of a systematic approach for the facade design of a high-rise nZEB, regarding energy and thermal comfort related performance, in the early design stages. The establishment of guidelines is expected to give an indication to designers/engineers for the performance of different façade design alternatives, supporting the decision making in the early design phase.

1.3. Objectives

General objective

- To establish guidelines, for early design stages, for the façade design of a nearly Zero - Energy high rise office building in the temperate climate, regarding energy and thermal comfort related performance. Within this scope, an integrated workflow is developed that allows the parametric design, the energy performance evaluation and optimization of different façade design alternatives of that type of buildings.

Sub-objectives

A. To determine the most effective combination of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate.

B. To determine the energy breakdown and the comfort performance for the best performing façade designs of a nearly Zero - Energy high-rise office building in the temperate climate.

Final products

1. Guidelines, for early design stages, for the façade design of a nearly Zero - Energy high-rise office building in the temperate climate, regarding energy and thermal comfort related performance.

2. An integrated workflow that allows the parametric design, the energy performance evaluation and optimization of different façade design parameters of a nearly Zero - Energy high-rise office building in the temperate climate, for early design stages.

3. Façade design proposal for a nearly Zero - Energy high-rise office building (reference building) in the temperate climate.

1.4. Boundary conditions

The research focuses on high – rise office buildings, with open-office floor plan and repetitive floors, in the temperate climate.

1.5. Research questions

Main research question

How can designers and engineers quantify the performance, regarding energy and thermal comfort, of different façade designs of a nearly Zero - Energy high-rise office building, in the temperate climate, in the early design stages?

Sub-questions

A. What is the most effective combination of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate?

B. What is the energy breakdown and the comfort performance for the best performing façade designs of a nearly Zero - Energy high-rise office building in the temperate climate?

1.6. Approach and methodology

The study uses the research through design methodology. It consists of five stages, as shown in the diagram in Figure 1.10. In the introduction, the context of the research and the problem statement are given, and based on that, the research questions are formulated. The literature review includes research for four main categories: nZEBs, energy-efficient high-rise precedents, façade design considerations and computational optimization. More specifically, the analysis of nZEBs entails research for the nZEB definition and initiatives, BENG regulations and comfort considerations. The literature sources consulted for this study consist of international conference proceedings, peer reviewed journal papers, regulations and academic research projects.

The analysis of the literature is used to determine the design requirements that the proposed façade should meet. Regulations and initiatives for energy-efficient buildings in the Netherlands, the building permit (Bouwbesluit), as well as regulations for the thermal comfort of occupants define the range of the variables of different façade design aspects to be tested in the optimization process. The outputs of the optimization include the energy demand and the generated energy per floor and total, and the breakdown of the energy demand, as well as the occupants' thermal comfort (%).

An existing high-rise office building, with open-office typology and repetitive floors, is used as a reference building for the simulation and optimization process: the Rotterdam Science Tower in the Merwe-Vierhavens (M4H) area, in Rotterdam, the Netherlands. Three floors with different building height are tested for the optimization. What is more, each one of the four facades of every floor

is modeled separately. In that way, it is possible to test the influence of the parameters on each zone of the building according to height, and on each façade.

The parametric modeling is developed in Grasshopper for Rhino, and for the energy simulation, Grasshopper (GH) and the Honeybee plug-in are used. Simulations in Design Builder software are also performed, in order to evaluate the results obtained from the Honeybee simulations. ModeFrontier software is used for the optimization and the post processing of the results. Sophisticated data analytics tools provided by the aforementioned software support the exploration of the big solution space, the evaluation of different design alternatives, and help extract the optimal and the sub-optimal designs.

The outcome of the optimization process is used in order to develop guidelines for the façade design of a nearly Zero - Energy high-rise office building in the temperate climate. The acquired knowledge from the optimization is also used for the development of facade design proposals for the reference building.
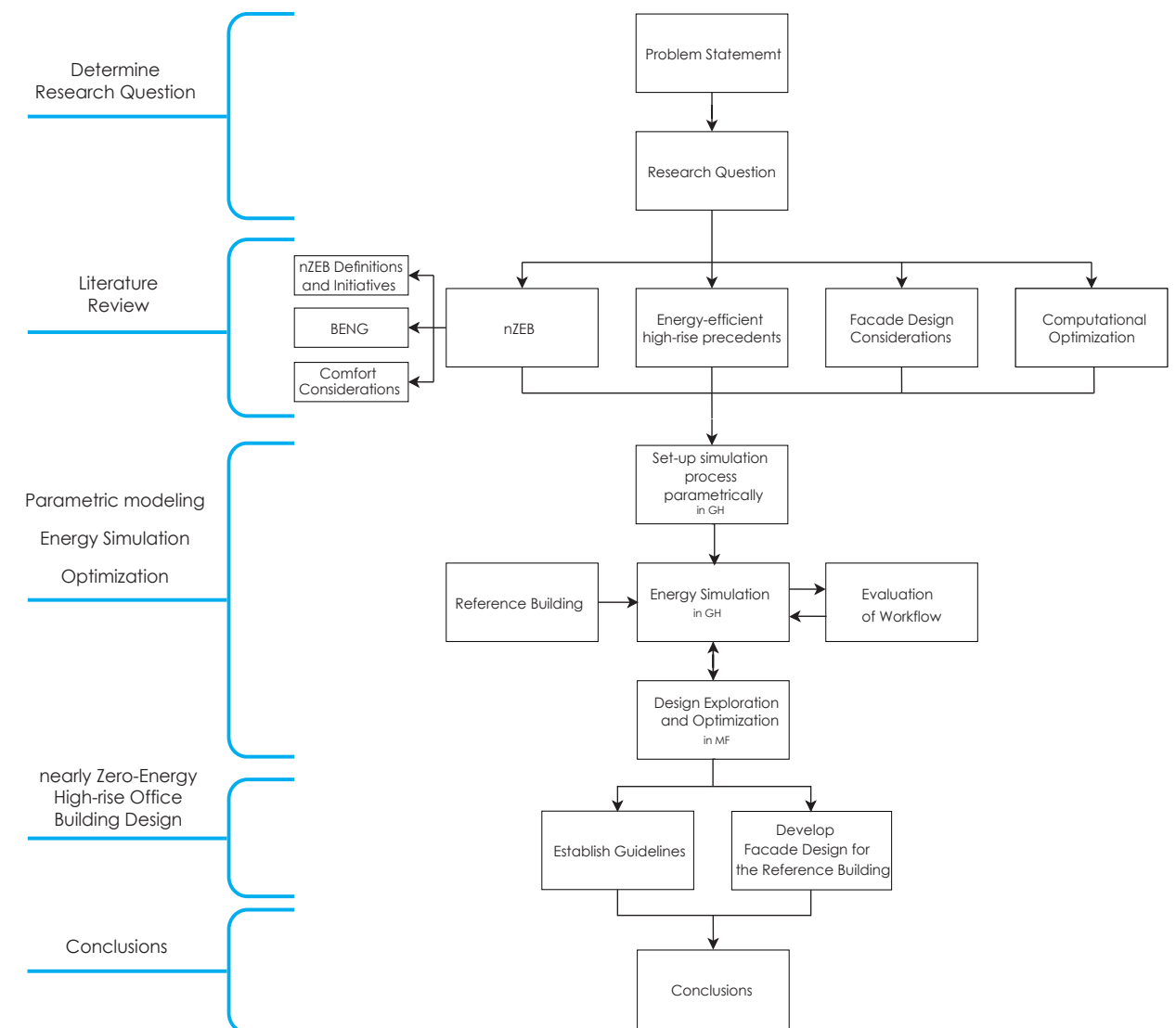

Figure 1.10: Methodology scheme

1.7. Planning and organization

Weekly Working Programme	November			December				January					February				March				April				May					June			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
P1																																	
Background and Methodology Research																																	
nZEB Definition and Initiatives																																	
BENG Regulations																																	
Facade Design Considerations																																	
Comfort Considerations																																	
Presentation - Report																																	
P2																																	
nZEB Characteristics																																	
Energy-efficient High-rises Precedents																																	
Computational Optimization																																	
Context-climate Analysis																																	
Set up Simulation Workflow																																	
Evaluate Results																																	
Presentation - Report																																	
P3																																	
Set up Optimization Workflow																																	
Guidelines Establishment																																	
Façade Design proposal																																	
Presentation - Report																																	
P4																																	
Conclusions																																	
Report																																	
Presentation																																	
P5																																	

1.8. Relevance

Societal relevance

Due to intense urban growth, strategic plans consider urban densification as the best solution for urban sustainability, and therefore, special attention is given to high rise buildings nowadays. In respect to international policies for nZEBs, guidelines for the façade design of high-rises in the temperate climate could be a great shift towards sustainable high-rises, with high levels of energy efficiency and indoor comfort.

Scientific relevance

From the designers' perspective, research for the particularities of the high rise typology is essential, in order for the designers/engineers to understand how different parameters affect the energy performance and the occupants' comfort. The establishment of guidelines for the façade design is expected to inform building technologists about the performance of different design alternatives, in early design stages, supporting the decision making for a high-rise nZEB, based on measurable criteria.

Additionally, the workflow that is developed within the scope of that research allows the designers/engineers design parametrically, assess the energy and comfort related performance and optimize different design parameters for high-rise nZEBs in the temperate climate. The definition that is developed can be modified and extended, in order to meet the demands for low-rise buildings, other types of buildings (e.g. residential buildings), and even other climates.

02
nearly Zero – Energy building

2.1. Review of nZEB definition and initiatives

Since the early 1990s, the concept of the net-zero energy building has been generally accepted as a technically feasible long-term goal, making use of the solar radiation incident on the building envelope, in order to satisfy all its energy needs. " A net zero energy building (Net ZEB) is normally defined as one that, in an average year, produces as much energy (electrical plus thermal) from renewable energy sources as it consumes. " (Athienitis & O'Brien, 2015, pg.1). Goals and requirements for the implementation of nZEBs have been discussed and proposed at international level. The chapter presents a review of the nZEB definition, focusing on the Directive on Energy Performance of Buildings (EPBD), developed by the European Union and the ASHRAE Vision 2020, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Considering Europe, the building sector accounts for 40 % of total primary energy consumption in the union. In order to reduce the union's energy dependency and greenhouse gas emissions, the European Commission has taken initiatives for the reduction of the energy consumption, as well as for the use of energy from renewable sources in the buildings sector. Therefore, it has introduced the Energy performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED). More specifically, the article 9(1) of the EPBD requires Member States to ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings (European Commission, 2010).The nZEB is defined by the EPBD recast as the following:

" 'nearly zero-energy building' means a building that has a very high energy performance... The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby " (European Commission, 2010, pg.18)

Member States must draw up national plans for increasing the number of nZEBs, which may include targets differentiated according to the category of building. In summary, the European commission has also defined the following elements to be included in the national plans of the member states:

(a) The definition of nearly zero-energy buildings, reflecting their national, regional or local conditions, and including a numerical indicator of primary energy use, expressed in kWh/m2 per year.

(b) Intermediate targets for improving the energy performance of new buildings.

(c) Information on the policies, and financial or other measures adopted for the promotion of nearly zero-energy buildings, including details of national requirements and measures concerning the use of energy from renewable sources in new buildings and existing buildings.

In that context, the directive has required all member states to describe the national plan, according to which, they contribute to reach the aforementioned goals. Apart from the primary energy use of a building, a recommendation has been made, in order to determine the energy performance of a building on the basis of "the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting" (European Commission, 2010, pg.18). Every member state has to define an energy performance indicator and a numeric indicator of primary energy use. According to Hermelink (2013), calculating the energy need of the building is the starting point for calculating the primary energy, and therefore, the energy need seems to be as an additional useful criterion for the energy performance of a nZEB.

Last but not least, another recommendation has been made for the improvement of the energy performance of buildings within the union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness (European Commission, 2010).

In the US, buildings consume 40% of the primary energy and 71% of the electrical energy. The American Society of Heating, Refrigerating and Air-Conditioning Engineers developed the ASHRAE Vision 2020, which describes the process for the design, the construction and the operation of net zero-energy buildings (NZEBs) by 2020 (ASHRAE, 2008). That document refers to different metrics, in order to define NZEB (ASHRAE, 2008):

-       The 'net zero site energy building' produces as much energy as it consumes. The energy is measured at the site, while the source of energy (fuel types), as well as inefficiencies of the grid are not taken into account.

-       The 'net zero source energy building' measures the primary energy: energy harvested from fuels and energy needed in order to deliver the extracted energy to the site. It also accounts for the energy that is lost during the process of generation, transmission and distribution.

-       The 'net zero energy cost building' refers to the energy utility bill over the course of a year. Building owners are usually interested in that metric, as they can use energy efficiency and on-site renewable energy in their business plan.

-       The 'net zero energy emissions building' accounts for the emissions produced by the energy needs of the building. Emissions-free energy (renewable energy) can be used to compensate for the produced emissions.

The ambiguity caused by the diversity of the existing metrics dictates the need for a single NZEB definition. ASHRAE and other relevant organizations, namely the U.S. Green Building Council (USGBC), the American Institute of Architects (AIA) and the Illuminating Engineering Society of North America (IESNA) use site energy measurements, in order to develop a calculation method that shows if a building fulfils the requirements for a NZEB.

2.2. BENG

In the Netherlands, the regulations regarding nZEBs build on the policy initiated in 1995, the"Energy Performance Standards for residential buildings and utility buildings". According to these regulations, minimum requirements were set for the energy performance of buildings, depending on the function. The energy performance of a nearly-energy-neutral building was determined on the basis of the NEN 7120 standards. As an indicator of the energy performance of the building, a dimensionless number was introduced: the Energy Performance Coefficient (EPC). It was considered that a completely energy-neutral building has an EPC value equal to zero (Rijksoverheid, 2012). The BENG regulations were introduced in order to meet the requirements set by the EPBD recast.

According to the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland - RVO) (Rijksdienst voor Ondernemend Nederland, n.d.), from January 1, 2020, for all new buildings, both residential and non-residential, applications for the environmental permit must meet the BENG requirements. For new government buildings, that applies from January 1, 2019, since the government has an exemplary role. According to BENG regulations, the energy performance for nZEB is determined on the basis of three indicators (DWA, 2016):

1. The maximum energy demand, in kWh per m², per year
2. The maximum primary fossil energy use, in kWh per m², per year
3. The minimum share of renewable energy, in percentages

Table 2.1 presents the originally proposed requirements for BENG indicators for different building functions (DWA, 2016). DWA and Nieman Consulting Engineers were commissioned by the National Enterprise Agency (Rijksdienst voor Ondernemend Nederland) in 2016, to conduct research into innovative techniques and concepts by that time, that can contribute to the energy performance of nZEBs, according to BENG requirements. When determining the BENG requirements, it became clear that it was more difficult for a number of categories of buildings to meet those requirements. These categories were the following, and further research was conducted regarding them:

- buildings higher than five floors, with emphasis on offices
- HBO schools, also higher than five floors
- hospitals
- residential buildings higher than five floors
- multilayer complexes with studios

Gebruiksfunctie	Energiebehoefte (BENG 1) [kWh/m².jr]	Primair fossiel energiegebruik (BENG 2)[kWh/m².jr]	Aandeel hernieuwbare energie (BENG 3) [%]
Utiliteitsgebouwen	≤ 50	≤ 25	≥ 50

Table 2.1: The originally proposed requirements for BENG indicators for different building functions. Adapted from: (DWA, 2016).

Among others, the following conclusions are important and relevant to the research (DWA, 2016):

- For higher buildings, the requirement for the share of renewable energy is generally more difficult to achieve, due to the small roof surface area. That also affects the primary fossil energy use (the share in the primary fossil energy use is lower compared to a lower building). In that research (DWA, 2016), the potentials of PVs integrated in the façade were investigated. These forms of integration contribute to the reduction of primary fossil energy use (BENG 2) and increase in the share of renewable energy (BENG 3). This technique applies a strong relationship with the design of the façade and the w/w ratio.

- Additionally, it is noteworthy that innovative options were also studied and described in that research, as measures to contribute to nZEBs, according to BENG requirements. Smart building components that were suggested include: switchable glass, switchable insulation, quadruple glass, and PCM in ceilings and floors. In order to calculate such techniques, dynamic calculations are needed, and as a result, guidelines and methods for dynamic calculations should be developed.

In order to meet the energy requirements and make a smooth transition towards nZEBs, in November 2018, the Netherlands Standardization Institute (NEN) published the revised BENG requirements (Lente Akkord, 2018) (see Appendix 01, Table a.01.1). Based on the feedback obtained from the construction industry, the renewable energy sector, environmental organizations and municipalities, the dutch ministry "Ministerie Binnenlandse Zaken en Koninkrijksrelaties" (BZK) announced the new BENG requirements in June 2019 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019). The latest BENG requirements regarding offices are presented in Table 2.2.

According to RVO (Rijksdienst voor Ondernemend Nederland, n.d.), the BENG 1 indicator refers to the building envelope and requires a low energy demand. The BENG 3 requirement ensures that the energy needed to meet the energy demand is produced by renewable sources as much as possible. Last but not least, the BENG 2 indicator requires the generation of the rest of the energy demand as efficiently as possible.

More specifically, BENG 1 aims at low building energy consumption and it takes into account facade design and construction parameters, such as the w/w, the degree of insulation, of cracking and of thermal bridges. It considers the combination of the parameters mentioned before, as well as the shape of the building. For BENG 1, heating and cooling loads are added to calculate the energy requirement, while a fixed "neutral" ventilation system is used for the calculations, meaning that no heat recovery is taken into account. Either renewable or fossil energy can be used in order to meet the energy demand. BENG 2 refers to the primary fossil energy use, which is calculated as the sum of heating, cooling, water heating and lighting, as well as fans. The primary energy use takes into account the system losses and the efficiency of the generators, in contrast to the energy demand, calculated with the BENG 1 indicator. If applicable, the renewable energy is subtracted by the primary energy, in order to calculate the BENG 2 indicator. In order to calculate the BENG 3 indicator, the renewable energy is divided by the sum of the primary energy use and the renewable energy (Rijksdienst voor Ondernemend Nederland, n.d.).

Gebruiksfunctie	Energiebehoefte (BENG 1) [kWh/m².jr]	Primair fossil energiegebruik (BENG 2)[kWh/m².jr]	Aandeel hernieuwbare energie (BENG 3) [%]
Kantoorfunctie	Indien Als/Ag ≤ 1,8 BENG 1 ≤ 90	≤ 40	≥ 30
	Indien Als/Ag > 1,8 BENG 1 ≤ 90 + 30 * (Als/Ag - 1,8)		

Table 2.2: The new BENG requirements for offices. Adapted from: (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

2.3. Comfort Considerations

As Jenkins et al (1990) have showed in their study, people spend more of their time (90%) indoors. During the main activities in an indoor space, the well-being of people is highly affected by health, comfort and safety conditions. There are four basic environmental factors in the indoor environment (Fig.2.1) that have a direct effect on the perception of the enclosed space through the senses, but also influence directly both users' comfort and health. These factors are the thermal comfort, the visual or lighting quality, the indoor air quality and the acoustic comfort (Bluyssen, 2009).

In the context on nZEBs, alongside with the targets for energy efficiency, buildings are expected to provide a comfortable environment to occupants, in order for them to develop their activities. It should be noted that there is a strong correlation between comfort and energy: if the users' needs for a comfortable environment are not met, they tend to adapt in the most convenient and responsive way, rather than in energy conserving ways (Cole and Brown, 2009). What is more, in a mechanically ventilated building, thermal comfort boundaries provide an indication to engineers regarding the extent up to which buildings should be heated or cooled (Bluyssen, 2009). As a result, comfort considerations should be taken into account throughout the design and operation of nZEBs.
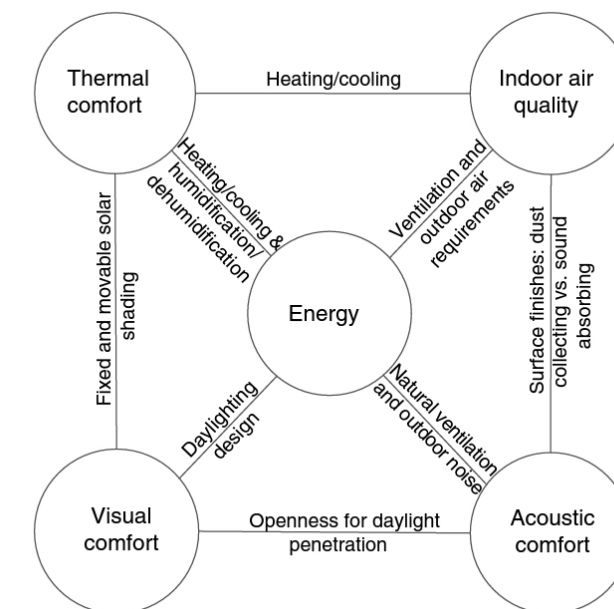

Figure 2.1: Relation between forms of comfort and building energy use (Athienitis and O'Brien, 2015).

Thermal comfort

Thermal comfort is usually used to indicate that the occupant does not experience too hot or too cold thermal conditions in a given environment. According to the psychological approach, thermal comfort is " that condition of mind which expresses satisfaction with the thermal environment " (ASHRAE, 2004, pg.2). Over time, two different approaches on thermal comfort have been proposed: climate chamber tests and field studies. Based on heat exchange processes of the body, chamber tests determined steady-state laboratory thermal comfort models and also standards, namely ASHRAE 55-199 and ISO7730. Field studies were used for adaptive thermal comfort models and standards, being ASHRAE 55-2010 (in America) and EN15251 (in Europe), as well as the dutch ATG guideline (Taleghani et al., 2013).

Steady-state thermal comfort models

Based on the heat-exchange method, many thermal indices were developed in the 20th century, considering the total thermal body comfort and also local thermal comfort aspects (e.g. draught, vertical air temperature difference and floor surface temperatures). The data for these indices derived from laboratory studies which put special focus on the heat exchange between a person and the thermal environment, and the required physiological conditions. Considering total body thermal comfort, one of the most common to use index, developed by Fanger (1970), is the Predicted mean vote (PMV), "… an index that predicts the thermal sensation of a person for a certain combination of environmental parameters and a known clothing resistance and metabolism." (Bluyssen, 2009, pg.135). The PMV uses a seven-point scale, from cold (–3) to warm (+3), and can be used to determine whether a given thermal environment complies with the specified comfort criteria. What is more, using the PMV enables the calculation of the range of operative temperature in which the thermal climate can be classified as acceptable (Bluyssen, 2009). Fanger also developed the PPD index, the predicted percentage of dissatisfied people who will be warm or cold in a certain environment. It can be calculated using the Fanger comfort equation (Fig. 2.2).

Although some existing standards specify only one level of thermal comfort, such as ASHRAE 55 (ASHRAE, 2004), other standards, namely ISO EN 7730 (ISO, 2005), CR 1752 (CEN, 1998) and EN15251 (CEN, 2005) recommend three categories, according to PPD and PMV values (Table 2.3) (Bluyssen, 2009).
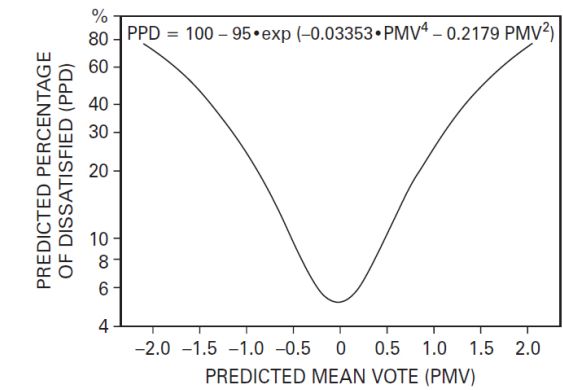

$$PPD = 100 - 95 \cdot \exp\left(-0.03353 \cdot PMV^4 - 0.2179\,PMV^2\right)$$

Figure 2.2: Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV) (Bluyssen, 2009).

Category	Thermal state of the body as a whole			Local discomfort Percentage of dissatisfied due to:		
	Predicted percentage of dissatisfied (PPD) (%)	Predicted mean vote (PMV)	Draught (DR) (%)	Vertical air temperature difference (%)	Warm or cool floor (%)	Radiant asymmetry (%)
A	<6	-0.2<PMV<+0.2	<15	<3	<10	<5
B	<10	-0.5<PMV<+0.5	<20	<5	<10	<5
C	<15	-0.7<PMV<+0.7	<25	<10	<15	<10

Table 2.3: Three categories of thermal comfort (CEN, 2005)

Adaptive thermal comfort models

Humphreys and Nicol (1998) challenged the validity of the steady-state method using field studies. The results of their studies indicated that the comfort temperatures in naturally ventilated buildings present a much wider range compared to those that the PMV-PPD models suggest, especially in summer months. Humphreys stated that steady-state thermal comfort models were unable to represent the capability of humans to adapt to changes of thermal conditions. He also proved that the indoor thermal comfort is related to the outdoor temperature. There is a clear division between occupants in buildings which operate on natural ventilation and in those on mechanical ventilation. The relationship between indoor comfort temperature and mean outdoor air temperature for free-running buildings is linear. On the contrary, for mechanical ventilated buildings that relation is more complex, as people in those buildings have different expectations (Taleghani et al., 2013). Occupants of heated and cooled buildings tend to adapt to the narrow, constant conditions provided by HVAC systems, in contrast to people in free-running buildings, who can tolerate a wider range of temperatures, merely affected by outdoor climate conditions (Bluyssen, 2009).

2.4. Guidelines for offices in the Netherlands

2.4. 1. Building physics requirements

The Nederlands Vlaamse Bouwfysica Vereniging Handbook (NVBV) establishes guidelines for building physics requirements in the Netherlands, and also defines requirements based on the desired quality level (basic, good, excellent), set by the engineer or the client (Nedelands Vlaamse Bouwfysica Vereniging, 2016). Regarding the building envelope, different aspects are addressed:

- Sound insulation
- Fire resistance
- Ventilation
- Daylighting and view
- Hygrical quality (thermal bridges, internal condensation)
- Water tightness
- Thermal insulation
- Air permeability
- Accessibility
- Feasibility
- Working conditions (safety)
- Sustainability

According to NVBV Handbook, the thermal insulation of the different building parts are presented in Table 2.4 and the performance levels for air permeability (infiltration rate) are shown in Table 2.5. Table 2.6 presents the suggested ventilation flow rates (m^2/h per person and m^2/h per floor area(m^2)). What is more, regarding the requirements for illuminance at a workspace, Table 2.7 shows the minimum lighting levels to be achieved (lux).

Thermische Isolatie	Kwaliteitsniveau		
	Basis	Goed	Uitstekend
Dichte delen	$R_{c;vloer}$ ≥ 3,5 m^{2}K/W $R_{c;gevel}$ ≥ 4,5 m^{2}K/W $R_{c;dak}$ ≥ 6,0 m^{2}K/W	$R_{c;vloer}$ ≥ 4,5 m^{2}K/W $R_{c;gevel}$ ≥ 5,0 m^{2}K/W $R_{c;dak}$ ≥ 7,0 m^{2}K/W	$R_{c;vloer}$ ≥ 6,5 m^{2}K/W $R_{c;gevel}$ ≥ 6,5 m^{2}K/W $R_{c;dak}$ ≥ 8,0 m^{2}K/W
Ramen en deuren	$U_{maximaal}$ ≤ 2,20 W/m^2 $U_{gemiddeld}$ ≤ 1,65 W/m^2	$U_{maximaal}$ ≤ 1,65 W/m^2 $U_{gemiddeld}$ ≤ 1,20 W/m^2	$U_{maximaal}$ ≤ 1,20 W/m^2 $U_{gemiddeld}$ ≤ 0,8 W/m^2

Table 2.4: Performance levels of thermal insulation. Adapted from: (Nedelands Vlaamse Bouwfysica Vereniging, 2016).

Geveldeel	Maximaal toelaatbare luchtdoorlaat bij de toetsingsdruk			
	Basis	Goed	Uitstekend	Eenheid
De gevel als geheel				
Met te openen ramen	1,80	1,44	1,15	10^{-3} m^3/s·m^2 geveloppervlakte
Zonder te openen ramen	0,50	0,40	0,30	10^{-3} m^3/s·m^2 geveloppervlakte

Table 2.5: Performance levels for air permeability, according to the assumptions of NPR 1088: 1999 nl. Adapted from: (Nedelands Vlaamse Bouwfysica Vereniging, 2016).

Ventilatie-efficiency = 2		Very low-polluting buildings		Low-polluting buildings	
		l/s	m3/h	l/s	m3/h
Categorie I		lucht pp	5	18	lucht pp	5	18
% ontevredenen	15	lucht/m2	0,5	14	lucht/m2	1	29
ppm CO2>buitenlucht	350	totaal per persoon	**32**		totaal per persoon	**47**
		totaal /m2	**4,1**		totaal /m2	**5,9**
		l/s	m3/h		l/s	m3/h
Categorie II		lucht pp	3,5	12,6	lucht pp	3,5	12,6
% ontevredenen	20	lucht/m2	0,35	10	lucht/m2	0,7	20
ppm CO2>buitenlucht	500	totaal per persoon	**23**		totaal per persoon	**33**
		totaal /m2	**2,8**		totaal /m2	**4,1**
		l/s	m3/h		l/s	m3/h
Categorie III		lucht pp	2	7,2	lucht pp	2	7,2
% ontevredenen	30	lucht/m2	0,3	9	lucht/m2	0,4	12
ppm CO2>buitenlucht	800	totaal per persoon	**16**		totaal per persoon	**19**
		totaal /m2	**2,0**		totaal /m2	**2,3**

Table 2.6: Ventilation flow rates based on NEN-EN 15251. Adapted from: (Nedelands Vlaamse Bouwfysica Vereniging, 2016).

soort ruimte, taak of activiteit	verlichtingssterkte op werkplek [lux]	Ra [-]
archiveren, kopiëren, e.d.	300	80
schrijven, typen, lezen, gegevensverwerking e.d. werken met een cad systeem conferentie- en vergaderzaal	500	80
technisch tekenen	750	80
receptiebalie	300	80
archieven	200	80

Table 2.7: Requirements for the illuminance levels on the work surface. Adapted from: (Nedelands Vlaamse Bouwfysica Vereniging, 2016).

2.4. 2. Comfort requirements

The first adaptive thermal comfort guidelines, ISSO 74, were introduced in the Netherlands in 2004, while ISSO 2014 is the updated version of that document and it is suggested for use by the building services and building physics community in offices and related buildings. The new guidelines are characterized as hybrid, because they are better tuned with the adaptive thermal comfort model, but they also take into consideration the static one.

It is noted that the suggested requirements needs to be met only during formal occupancy hours, and only in the zone of occupancy, usually at a height of 0.6 m. The user of these guidelines should determine firstly the type (a or b) of the examined situation, and secondly the classification level to be used (Class a, b, c or d). Type a includes free-running buildings/spaces with operable windows, where occupants have also other adaptive opportunities, such as a non-strict clothing policy. Type b, on the other hand, refers to centrally controlled cooling. Since a mixed-mode ventilation system is used for the optimization conducted in that research, as described later on, type b is selected for the case-study building. Furthermore, the research refers to new buidlings, with normal level of expactation, and as a result it uses the guidelines of class b. Figure 2.3 presents the recommended operative temperature (between the black bold lines), as well as the recommended set temperatures (dashed lines), for class b buildings.
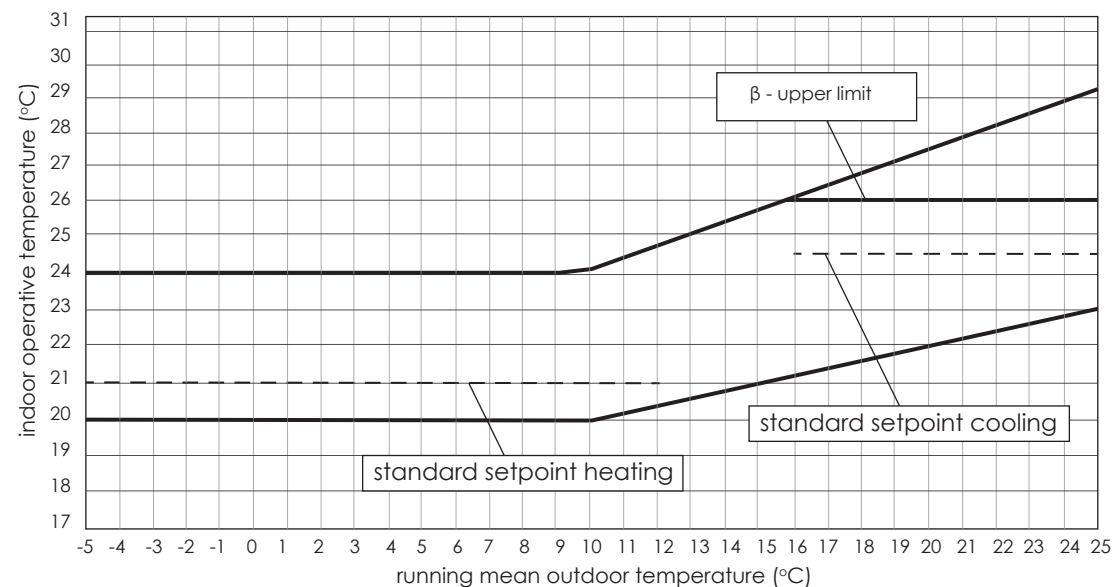

Figure 2.3: The indoor operative temperature in relation to the running mean outdoor temperature, according to the requirements of class B (ISSO 74: 2014) (A.C.Boerstra, J. van Hoof, 2014).

03

Façade design considerations

3. Façade design considerations

Being the mediator between indoors and outdoors, the building envelope affects considerably the building energy use and the indoor climate. Therefore, designing the building envelope in an energy conscious way is one of the best ways for saving energy in new building projects (Konstantinou, 2014). In every project, at early design stages, the usage requirements and climate conditions should be analyzed, and then, the technical and functional characteristics of the façade should be established. In order to achieve high levels of energy efficiency, one should first define the design parameters which have the biggest effect on the building energy performance, and then optimize them (Raji, Tenpierik, & Dobbelsteen, 2016). The research takes into consideration current literature regarding the optimization of building envelope design parameters, with the goal of energy-saving and enhancing indoor comfort, focusing on the temperate climate (Table 3.1). Based on the literature review, the basic parameters that can affect the envelope performance are analyzed later on:

- Window to wall ratio
- Wall (opaque part)
- Glazing type
- Thermal mass
- Wall air tightness
- Shading strategy
- Ventilation

The research focuses on the energy efficiency and occupants' thermal comfort as a result of the optimization of different envelope's design parameters. However, it should be noted that for an holistic approach, when designing a façade, different aspects needs to be considered: environmental control, financial costs, client needs and occupants' comfort.

3.1. Window to wall ratio

The selection of window-to-wall ratio of a facade has an impact on peak heating and cooling demand and energy consumption, daylight level and electricity demand for lighting (Tzempelikos, Athienitis, & Karava, 2007). In their research focused on office buildings in the temperate climate, Raji et al. (2016) found that the optimal w/w ratio is around 50%, considering a low U-value for both the glazing and the exterior wall. These values lead to low heat losses during winter and also low heat gains during summer. These results agree with the research results of Ochoa et al. (2012), focusing also on offices for the same climate: the optimum values for the w/w ratio for the east and the west orientation have a range between 50 and 60%, considering a double-pane clear glass.

3.2. Wall (opaque part)

The thermal performance of the building envelope is determined by the thermal properties of its materials, being the absorptance or emittance of solar heat, as well as the overall U-value of the corresponding component including insulation. Being a major contributor towards achieving energy efficiency, thermal insulation is a material or an assembly of materials that lessens the heat flow rate by conduction, convection, and radiation, due to its high thermal resistance (Al-Homoud, 2005).

Three indicators, namely the thermal conductivity (λ), measured in W/m-K, the thermal resistance (R-value), measured in m^2-K/W, and the thermal transmittance (U-value), measured in W/m^2-K, are used for describing the heat transfer through a thermal insulation material. Requirements for the energy performance of the closed parts of the façade usually refer to the thermal resistance of the insulation. The thermal resistance is the rate that heat is transferred through a unit surface area of the material, multiplied by the difference in temperature either side of the material (AEA, 2010). Higher R-values provide better insulation. Table 3.2 presents the thermal conductivity values for typical insulation products, at different densities and temperatures. Common commercial building thermal insulation types are classified into organic and inorganic/mineral types. Another type includes artificially manufactured materials, often called as high performance thermal insulation materials (Konstantinou, 2014).

Studies	Research objective	Location	Tested parameters
Capeluto and Ochoa (2014)	to determine and rank energy-efficient retrofitting solutions	cities from North to South Europe	parameters realted to: glazing, insulation, shading strategy, solar absorptance, mechanical ventilation and summer night ventilation
Konstantinou and Knaack (2012)	to determine the energy effect of building envelope components and installation systems on refurbishment of middle-rise residential buildings constructed in the 1960s	the Netherlands and Germany	parameters related to: external walls, basement, roof, windows, balcony, ventilation and heating sources
Ochoa et al. (2012)	to determine the suitability of combined optimization criteria on window sizing procedures for low energy consumption with high visual comfort and performance	temperate climate	w/w ratio, orientation
Raji (2016)	to assess the role of building envelope design strategies on reducing the energy consumption of high-rise office buildings in temperate climates	the Netherlands	parameters related to: glazing type, w/w ratio, shading and roof
Verbeeck and Maamari (2004)	to determine the optimal balance between costs and energy benefits of refurbishment strategies	Belgium	parameters related to: insulation, window (frame and glazing type), heating system and renewable energy systems

Table 3.1: Literature review regarding the optimization of building envelope design parameters, with the goal of energy-saving and enhancing indoor comfort, focusing on the temperate climate.

Insulation from organic material

For the last decades, several insulation materials made of organic, renewable resources can be found in the market. Nowadays, the fibres, made of renewable resources, that are most often used to produce insulating materials, are the following: flax, wood, cellulose, grass, reed, seaweed, granulates from rye or cork, and sheep-wool (Al-Homoud, 2005). Regarding the applicability of that type of insulation, national building codes have approved the insulation materials made of renewable resources (Konstantinou, 2014).

Insulation from inorganic material

Mineral sources are used to produce that type of insulation. The insulation materials can be found in different forms such as foam, mineral wool and loose-fill, and their biggest advantage is that they are highly fire – resistant and recyclable, compared to other insulation types. For example, glass and stone wool insulation are common types of mineral wool products. Foamy mineral insulators include, among others, cellular or foamed glass and perlite, in form of loose fill. The former is ideal as a barrier against soil humidity, and the latter is a highly efficient, low-density insulator (Konstantinou, 2014).

Type of insulation	Nominal density (kg/m^3)	Mean Temperature (°C)	Thermal Conductivity (W/mK) at nominal density
Glass mineral wool	10-200	10	0.037-0.031
Rock mineral wool	20-200	10	0.033-0.034
Expanded polystyrene (EPS)	15-30	10	0.038-0.033
Extruded polystyrene (XPS)	28-45	10	0.027-0.026
Phenolic foam	35-60	10	0.018-0.022
Polyisocyanurate foam (PIR)	32-50	10	0.023
Polyurethane foam (PUR)	35-50	10	0.023
Cork	112	10	0.038
Exfoliated vermiculate	109	10	0.066

Table 3.2: Thermal conductivity values for typical insulation products, at different densities and temperatures. Adapted from: (AEA, 2010).

Other high performance thermal insulation materials

Vacuum insulation panels (VIPs) are artificially manufactured, and they are considered as one of the most promising high performance thermal insulation types nowadays. Applying a vacuum to an encapsulated micro-porous material achieve exceedingly higher thermal performances than still-air. The evacuation of air hinders heat transport by convection and conduction, and therefore, the evacuation of air improves significantly the insulating properties of the material (Baetens et al., 2010). Although that type of insulation can lead to a high reduction of the energy demand with thin constructions, costs are still quite high: VIPs are approximately 10 times more expensive than fibre or solid-foam insulation (Konstantinou, 2014).

3.3. Glazing type

Glazing and Frame - U-value

The U-value refers to the heat transmission from one side of the glass to the other, and the lower the value, the better the performance. The most common building glass in the market is the insulated glass unit (IGU), which consists of multiple glass panes and a space between them. The number of glass panes in the assembly, the thickness of the glass and the spacing between the panes, as well as the type of gas or vacuum in the spacing determines the performance of the glazing. It is suggested taking into account both the glass and the frame U-value, when selecting a glazing product (Syed, 2012). Table 3.3 presents the U-value of different types of glazing.

Type of glazing	Number of panes	Dimensions (mm)	Gas infill	U-value (W/m2-K)
Single glazing	1	4	n/a	5.6
Double glazing	2	4-6-4	Air	3.3
Double glazing	2	4-12-4	Air	2.8
Triple glazing	3	4-6-4-6-4	Air	2.3
Triple glazing	3	4-12-4-12-4	Air	1.9
Double with Low E	2	4-6-4	Air	2.5
Double with Low E	2	4-12-4	Air	1.7
Triple with 2 Low E	3	4-12-4	Air	1.6
Triple with 2 Low E	3	4-6-4-6-4	Air	1.0
Double with Low E and Argon	2	4-6-4	Argon	2.1
Double with Low E and Argon	2	4-12-4	Argon	1.3
Triple with 2 Low E and Argon	3	4-12-4	Argon	1.2
Triple with 2 Low E and Argon	3	4-6-4-6-4	Argon	0.8

Table 3.3: U-value of the different glazing types (ISO10077-1, 2006)

Glazing - g-value

The solar heat gain coefficient refers to the fraction of heat from the sun that comes into the building, through the glazing. The g-value has a range from 0 to 1, and the higher the value, the higher the solar gain. In Europe, this coefficient is expressed with the total solar energy transmittance (g-value), and in America, with the solar heat gain coefficient (SHGC). The solar heat gain coefficient should be determined accordingly, so that a balance between winter heat gains and summer benefits is achieved. Nowadays, spectrally selective low E coatings are commonly used in order to reduce the g-value. Different types of low E coatings are available, including low, moderate and high solar gain (Syed, 2012).

Glazing - Visible light transmittance (VT)

The visible light transmittance refers to the amount of visible light that enters the building, through the glazing. It is the fraction of the visible spectrum of light that is transmitted through the glazing. The higher VLT value, the more light comes into the building. A high VT value leads to a high daylight level, thus minimizing the lighting load (Syed, 2012).

Glazing - Light to solar gain ration (LSG)

In the past, tints or coatings added to the glazing in order to reduce the g-value, also reduced the VT-value, which was undesired in most cases. However, nowadays new methods allow the separation of these two values: high performance glass with tints or low-solar gain, low-E coatings achieve a low g-value, without minimizing the visible transmittance (Efficient Windows Collaborative, n.d.). The Light to solar gain ratio (LSG) is the VT value divided by the g-value, and it is considered as an important measure of the facade performance. Glazing with a high LSG value indicates lower solar heat gain and higher visible light transmittance, while glazing with a low LSG value is indicative of very little heat gain and light entering the room (Syed, 2012).

Type of glazing	LSG	g-value	VT-value
Double-glazed unit with clear glass	1.13	0.7	0.79
Bronze-tinted glass in a double-glazed unit	0.90	0.5	0.45
Double-glazed unit with a high-performance tint	1.79	0.29	0.52
Clear double-glazed unit with a low-solar-gain low-E coating	2.37	0.27	0.64

Table 3.4: The light to solar ratio (LSG) for different types of glazing (Efficient Windows Collaborative, n.d.).

3.4. Thermal mass

The thermal mass of the building envelope reduces heat gain by capturing and delaying the entry of heat into the building. The internal mass of the building envelope, the floors or ceilings stores the excess heat, coming from the sun or internal loads of the building, and releases it during unoccupied or cooler periods. More specifically, the time lag is a characteristic of the material thermal mass, and it is defined as the length of time from when the outdoor temperature reaches its peak until the indoor temperature reaches its peak. Each façade, according to orientation, and the roof require different material thermal mass, because of different peak heat gain time (Al-Homoud, 2005).

Syed (2012) connects the thermal mass with two processes, being the reduction in peak cooling load and the reduction of energy. Considering the former, shifting the load to the nonpeak times does not result in the reduction of the energy consumption, but it does reduce the instantaneous demand for electrical power. Given that the cost of electricity is the highest at the peak load hours, shifting the cooling load can lower the electric utility costs. When following the diurnal cycle, the thermal mass of the façade can be used during winter time in order to capture heat from the daytime solar energy, and release it at night, reducing that way the heating demand. Similarly at summer, the envelope can store the internal load during the night and release it during the day for cooling (Syed, 2012).

3.5. Air tightness

The air tightness is one important aspect affecting the energy performance of the building envelope, merely due to the fact that it affects the infiltration rate, which is the movement of air through leaks, cracks, or other openings in the façade. Apart from the energy-use aspect, infiltration impacts also the transport of contaminants between indoor air and outdoor air. Generally it is desirable to decrease air tightness, so that the building energy use is reduced, but in order to provide appropriate indoor air quality, adequate ventilation should be provided as well (Sherman, 2014).

3.6. Shading strategy

Solar screening provided by shading devices controls solar gains to avoid overheating. The shading factor F_c of the solar screening and the total solar energy transmittance g of the glazing determines the energy entering the building through the envelope. The position of the solar screening affects merely its effectiveness. External shading systems can be three and five times more efficient than internal systems. Solar screening installed in the glazing cavity can also be very effective. However, other factors, such as the facade orientation, the desired transparency of the facade, prevailing winds, daylight requirements, initial and maintenance costs, determine also the selection of the type of the shading system (Hausladen et al., 2006).

External shading systems are the most effective systems, as they block the radiation before reaching the envelope. External venetian blinds made by aluminium, plastic or wood can achieve a shading factor of 0.1. Due to their exposure to outdoor environmental conditions, the initial and maintenance cost are much higher compared to other shading types (Hausladen et al., 2006). Examples of external solar screening are overhangs, vertical or horizontal louvres, venetian blinds, sliding shutters and awnings.

The solar screening effectiveness of internal systems is worst compared to external systems: theoretically they can reach a 0.3 shading factor value, but in practice it is noticed that these values cannot be achieved due to dirt. However, the internal systems are protected from the weather, decreasing significantly the initial and the maintenance cost. Internal shading devices can also heat up and radiate the heat, affecting negatively the thermal comfort. Examples of internal shading systems include film roller blinds and highly reflective venetian blinds (Hausladen et al., 2006).

Shading systems in the glazing cavity are highly efficient because they are not exposed to weather conditions. They can reach F_c-values as low as 0.15. This type of shading can be either fixed systems, for example prints, textures or louvers, or movable systems, such as louvers (Hausladen et al., 2006).

The shading systems, mainly the blinds, can be controlled either manually or by the building management system (BMS). In order to maximize the effectiveness of the motorized blinds, they can be automated to respond to sun and light. Optimizing solar heat gain and daylight is challenging, as the solar radiation and visual light transmittance varies hourly, based on the position of the sun and seasonality. Therefore, customized algorithms are needed, in order to determine the schedule of the shading system, so that both functions can be integrated (Syed, 2012).

3.7. Ventilation

Natural ventilation strategies

Although comfort requirements can be fulfilled by mechanical ventilation, natural ventilation is suggested in most cases, as it offers to occupants the feeling of well-being. Other advantages of natural ventilation are related to reduced technical complexity, reduced energy demand and saving of room space considering installations. Openings in the façade admit air, which enters the building, moved by buoyancy or the wind or both of them (Hausladen et al., 2006).

Ventilation by thermal buoyancy uses vertical air movement, caused by differences in air temperature, due to differences in temperature between inside and outside air. The effective height and the temperature difference affect this phenomena. For that reason, windows in the balustrade and skylight area are preferred compared to a centrally located window (Hausladen et al., 2006).

Ventilation by the wind occurs when the openings in a room or a building are placed in different pressure zones, causing the air to flow from the positive to the negative pressure zone. In that case, air exchange is affected merely by the wind speed. What is more, changes in wind pressure due to wind turbulence can also cause intensive air change (Hausladen et al., 2006).

Mixed-mode ventilation strategies

Especially for high-rise office buildings, it is extremely rare to rely on only on natural ventilation. Most buildings of this type use mixed-mode ventilation systems. These hybrid systems result in considerably energy savings over the year, when the building operates on natural ventilation. The mixed-mode ventilation strategies can be zoned or complementary. The system is categorized as zoned when some zones/areas of the building rely on mechanical ventilation and other on natural ventilation. When both types of ventilation have been incorporated in the design of the building, then the ventilation strategy is classified as complementary (Hausladen et al., 2006).

04
Energy efficient high-rise precedents

4. Energy efficient high-rise precedents

The analysis of precedents aims to give insight into the strategies used by designers/engineers for designing energy-efficient high-rise in the temperate climate. The building use (offices), building height and location are the criteria for selecting the following examples. Another reason for selecting these buildings is the available information concerning the design strategies followed. The analysis of the buildings is divided in three main categories, building geometry, building envelope and building services, in order to allow the comparison between the examples.

4.1. Commerzbank

Location: Frankfurt, Germany
Building Use: Office
Building Height: 259m
Stories: 56

Figure 4.1: Commerzbank, Frankfurt, Germany (Foster+Partners, n.d.-b)

Building geometry

The high-rise building is located centrally in Frankfurt, in a dense urban environment, the Frankfurt am Main district. The tower has a set-back of a six-story-high base, which allows its integration with the adjacent low-rise buildings. The plan of the tower has a triangular shape with a central atrium running the full height of the building. The three corners of the building facilitate the vertical circulation and auxiliary rooms, while the office spaces are developed in parallel to the three edges of the triangle. The offices are organized vertically on 12-storey units, on top of each other, all connected to the central atrium. Each unit has also access to a four-storey sky-garden, each one located on one of the three main facades of the building. The office wings are split with a central corridor, and therefore half offices face the inner atrium, while the other half face the exterior. The atrium is divided also into four zones, through the use of glass and steel diaphragms, in order to isolate each zone. In that way, the diaphragms limits potential stack pressures and smoke spread in the central atrium, and also allow the independent ventilation of every unit.

Building envelope

The outward-facing offices have a double skin façade (DSF), which allows air from the cavity to enter the rooms. The outer layer of the DSF is a single pane of laminated glass, which protects the building from wind and rain, while in the interior the façade system consists of inward bottom-hinged double-glazed windows. The DSF system has a cavity of 200mm, 1.5m horizontal continuity and 2.4m height (between floor spandrel panels). The external façade has a 125mm continuous slot above and below the glass part, which lets the air coming in and out of the cavity, while strips with an aerofoil section, positioned alongside the length of the slots, improve the air-flow. In that way, the double skin façade has two mayor roles: 1. it controls wind-driven ventilation in the offices and 2. it allows the exhaust of air from the spaces, since the air warms in the cavity by the stack buoyancy effect.

The inward-facing offices have bottom-hinged windows facing the atrium. The rooms are naturally ventilated, since the air moves through the atrium to the sky-gardens or inversely. The latter have a 14-meter high façade with large motorized pivoting windows at the top and the bottom for air-intake and extraction.

Building services

The building uses a mixed-mode ventilation strategy, giving emphasis on natural ventilation, which is used 60% of the year, in order to provide thermal comfort to occupants. For the offices, single-sided ventilation strategy is applied, while for the atrium, both cross and stack ventilation is used, as described before. The spiraling pattern of the sky-gardens allows natural ventilation to occur regardless the wind direction, as there is always both a windward garden to admit air, and a leeward garden to exhaust it. That is why the strategy followed for the office in the inward side of the building is more successful, and those spaces can use

natural ventilation through the whole year.

When extreme weather conditions do not allow natural ventilation, mechanical ventilation is used for the office spaces. During winter time, panel radiators placed below the external windows provide heating, and during summer, a water-filled cooling system, integrated in the ceiling, provides cooling.

A central Building Management system (BMS), controlling the window, the artificial lighting, the motorized shading system and the air-conditioning ensures high energy efficiency and comfort levels. What is more, the building uses a grey water management system, in order to save water for flushing the toilets (Noble, n.d.).

4.2. 30 St.Mary Axe

Location: London, UK
Building Use: Office
Building Height: 180m
Stories: 42

Figure 4.2: 30 St.Mary Axe, London, UK (Foster+Partners, n.d.-a)

Building geometry

The building stands in London's primary financial district, the City of London. It has a circular profile in plan view, the diameter of which varies per floor: the first floor has a diameter of 50m, while the seventieth floor has a diameter of 17m. Six triangular atria, placed radially in every floor, form the rectangular-shaped office spaces. The circular central core facilitates vertical circulation and services. Each floor is rotated by 5 degrees, regarding the floor below, and as a result the atria are developed in a spiral shape around the building. These atria are separated every two or six floors, creating zones, the so-called "office villages".

Building envelope

Both the offices and the atria have a DSF, in order to be protected by strong winds. The atria have motorized, triangular-shaped windows, organized in groups of four top-hung and four bottom-hung in each floor alternatively. On the contrary, office spaces are not naturally ventilated directly through the exterior facade. Each of these spaces are connected to atria (one or two), and operable windows in the adjacent facades introduce fresh air to the offices. In that manner, either single-side ventilation or cross ventilation is induced. The outermost layer of the facades in the offices is a clear, double-glazed low-E pane, and the innermost layer is a single-glazed pane. The cavity, having a range of 1 to 1.4 meter width, includes dynamic blinds for solar and daylight control. The DSF extends from floor to floor and its length horizontally depends on the position of the structural elements.

Building services

The building is designed to run on natural ventilation for 40% of the time annually, but when weather conditions do not allow it, mechanical air-conditioning is activated. Both the aerodynamic building shape and the plan layout enhance natural ventilation. The air flowing around the building accelerates, resulting in high pressure differences, which allow an effective cross-ventilation. Additionally, since some atria are located in the windward side of the building and some in the leeward side, stack ventilation is induced.

The mechanical ventilation strategy works in a different way compared to the natural one. Air-handling units (AHU) located in each floor ceiling allow the users to control the conditions of their working environment independently from other offices. At each floor level, slits between the glazing panes introduce air to the AHU in the ceiling void. Part of the exhaust air is brought back to the AHU (heat recovery) and the rest is driven to the cavity of the DSF. During summer, that air decreases the temperature of the glass and the blinds, while at winter it reduces the chilling effect of the glass panes. A BMS controls the operation of the windows, based on outdoor and indoor temperature, humidity levels and wind speed. It also controls the operation of blinds in the cavity of the DSF, so that the cooling load is minimized, while sufficient natural light is let in (Wood & Salib, 2013).

4.3. Post Tower

Location: Bonn, Germany
Building Use: Office
Building Height: 163m
Stories: 42

Figure 4.3: Post Tower, Bonn, Germany (Jahn, n.d.)

Building geometry

In plan view, the building has an ellipsoid shape, penetrated by a linear atrium. The atrium is developed in the west-east axis, while the elliptical parts face north and south. The ellipsoid segments facilitate the office spaces in the perimeter, and conference rooms and staircases towards the center of the ellipsis. The atrium serves as corridor, facilitating the elevators.

Building envelope

Both the north and the south façade have a DSF, which consists of an outer single-glazed pane, sun shading system in the cavity and an inner layer of double-glazed pane, filled with argon. The outer skin continues horizontally and vertically without being segmented, while the cavity of the DSF is divided vertically every 9 floors approximately. The outer glass façade is hanged by stainless steel sections, fixed in the concrete slab of every floor. The south façade has sloped glass panes with vents at the bottom, while the north façade is flat, consisting of vertical panes with vents at the lower part of each unit. The south facade requires a bigger cavity in order to exhaust the heat compared to the north side, as the former collects more solar radiation annually. Therefore, the cavity is 1.7m wide in the south facade, and 1.2 m wide in the north facade.

Building services

The building uses a mixed-mode ventilation strategy: the meeting rooms and the conference spaces are conditioned mechanically, the office spaces are either naturally or mechanically conditioned, while the atrium runs only on natural ventilation. The natural ventilation strategy lies on the premise that fresh air is introduced to offices from the DSF and it is exhausted by the central atrium. Both cross and stack ventilation is applied. Air enters the offices through the DSF and then it flows from the office spaces to the corridor through vents in the partition walls. The air is led to the atrium through the ceiling cavity and finally it is exhausted from operable windows of the higher floors. Fresh air is also introduced by windows of the lower levels, in order to enforce the stack effect in the atrium.

Fan coil units and radiant ceilings condition the office spaces in extreme weather conditions. Air from the DSF is led to the fan coil units, where it is heated or cooled based on demand. The units are located below the floor, close to the façade. Radiant heating/cooling is also provided by the exposed concrete in the ceilings, which contain pipes for the circulation of hot/cold water. The building has zero cooling demand, as the energy source for the HCAV system comes from the heat exchange with cold water from the Rhine river. What is more, district heating provided by the city of Bonn, ensures low values for heating demand.

A BMS controls the operation of the vents in the outer skin façade, responding to temperature, noise and wind speed changes. It also controls the operation of

the windows in the inner skin for ventilation purposes. Additionally, the provision of cold water in the concrete slabs, the sun shading system and the artificial lighting are controlled by the BMS as well. The blinds in the cavity of the DSF are highly-reflective, and they are used in order to minimize both the direct solar gain and glare (Wood & Salib, 2013).

4.4 Comparison of the examples

In summary, as expected, some common design strategies are to be found among the analyzed examples, since they were designed for similar climate (Table 4.1). All studied buildings feature a double skin façade with sun-shading in the cavity. A mixed-mode ventilation system, in compliance with a BMS, is applied to all of them, in order to minimize the energy demand and provide comfort to occupants. The use of atria or sky gardens in all three examples assists natural ventilation through the stack effect. Additionally, the studied buildings have a BMS that controls the operation of the windows for natural ventilation, according to various indicators, such as outdoor/indoor temperature, humidity levels and noise. The BMS also controls the motorized blinds in order to avoid overheating and/or to protect from glare. Efficient types of HVAC systems ensure low primary energy levels as well.

Although that the studied buildings have a low energy consumption, they do not produce energy, for example with the use of solar collectors. That is a common strategy followed by high rise buildings in countries which collect more solar radiation, in order to minimize the energy demand. Since current regulations for nZEBs require the production of renewable energy, in order to cover part of the primary energy use, the research investigates the potential of BIPVs mounted on the walls of the high-rise building.
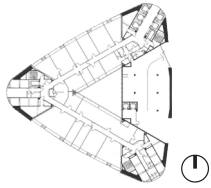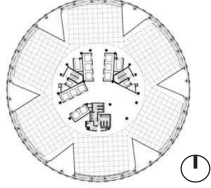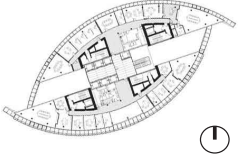
	Commerzbank	30 St.Mary Axe	Post tower
Building Geometry			
Building Envelope	DSF **outer layer:** single pane, laminated glass **inner layer:** inward bottom-hinged double-glazed windows **cavity width:** 0.2m **horizontal continuity:** 1.5m **vertical continuity:** 2.4m (between floor spandrel panels) Motorized blinds in the cavity	DSF **outer layer:** sclear, double-glazed low-E pane **inner layer:** a single-glazed pane **cavity width:** 1-1.4m **horizontal continuity:** varies (between members of the diagrid structure) **vertical continuity:** 4.15m (floor to floor) Motorized blinds in the cavity	DSF **outer layer:** single pane, laminated glass **inner layer:** inward bottom-hinged double-glazed windows **cavity width:** 20mm **horizontal continuity:** 1.5m **vertical continuity:** 2.4m (between floor spandrel panels) Motorized blinds in the cavity
Building Services	Mixed-mode ventilation Natural ventilation: single sided ventilation for offices, and cross and stack ventilation for the atrium Mechanical ventilation: panel radiators placed below the external windows and a water-filled cooling system, integrated in the ceiling BMS: controls the windows, the artificial lighting, the motorized shading system and the air-conditioning	Mixed-mode ventilation Natural ventilation: cross ventilation for offices, and cross and stack ventilation for the sky gardens Mechanical ventilation: AHU located on each floor and BMS: controls the windows and the motorized shading system	Mixed-mode ventilation Natural ventilation: single sided ventilation for offices, and cross and stack ventilation for the atrium Mechanical ventilation: panel radiators placed below the external windows and a water-filled cooling system, integrated in the ceiling BMS: controls the windows, the artificial lighting, motorized shading system and air-conditioning

Table 4.1: Comparison of the design strategies followed for the studied buildings (Wood & Salib, 2013).

Images illustrating the floor plans (from left to right):

Figure 4.4: Commerzbank, Frankfurt, Germany (Foster+Partners, n.d.-b)

Figure 4.5: 30 St.Mary Axe, London, UK (Foster+Partners, n.d.-a)

Figure 4.6: Post Tower, Bonn, Germany (Jahn, n.d.)

05
Computational optimization

5. Computational optimization

Mathematical optimization refers to the identification of the best element among a set of alternatives, based on a specified objective. In recent decades, computational means, such as parametric design and performance simulation tools integrated in the design process, has led to an increase of interest for optimization processes in the discipline of architecture (Wortmann et al., 2017). Sariyildiz (2012) presented the performative computational architecture framework (PCA), in order to support the design process. The PCA framework consists of three looped parts: form generation, performance evaluation and optimization (Fig.5.1). For the form generation phase, parametric design is used in order to develop design alternatives, instances of the design, by combining the variables set during the parameterization process. The total of all the generated alternatives constitute the solution space of the parametric model.
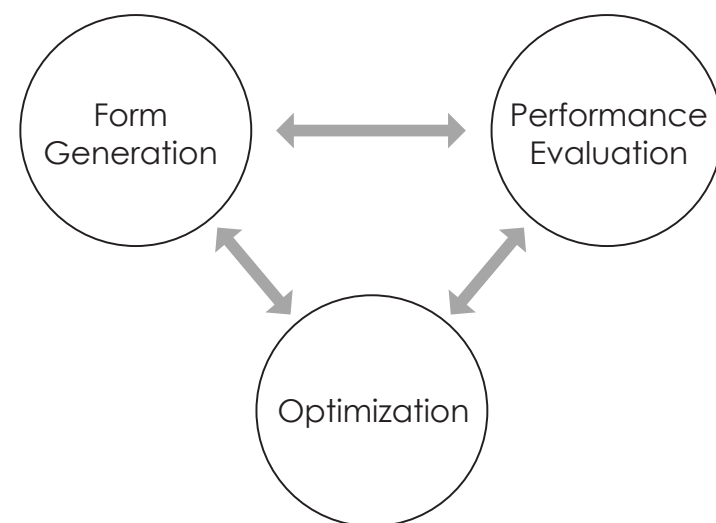
Figure 5.1: Performative computational architecture framework (PCA). Adapted from: (Sariyildiz, 2012).

Among all the potentials that parametric design has, that thesis put emphasis on the automatic generation of design alternatives, based on the concept of performance-oriented design. Within that scope, each design instance can be evaluated according to selected performance indicators with the use of simulation tools. Additional computational means, such as optimization algorithms automate the selection process of the best-performing instances within the solution space. The greatest advantages of the automatization driven by algorithms compared to manually perform that process are first of all, the ability to search in much larger solution spaces and secondly, the systematic exploration provided by the algorithms (Turrin, 2014). Figure 5.2 shows the most typical strategy applied for simulation-based optimizations in building performance studies (Nguyen, Reiter, & Rigo, 2014).
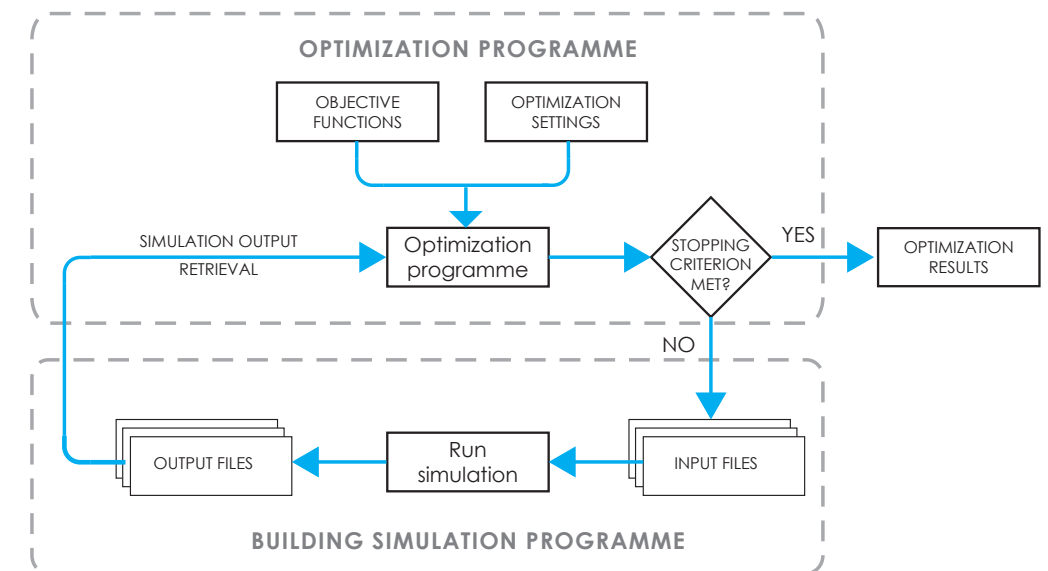
Figure 5.2: The most typical strategy applied for simulation-based optimizations in building performance studies (Nguyen et al., 2014).

5.1. Optimization algorithms

The most important aspects of the optimization algorithms are the robustness, the accuracy and the convergence rate. The robustness describes the ability of the optimization algorithm to converge to the global optimum, without being trapped at a local optimum. The accuracy refers to the ability of the optimizer to reach the objective function as close as possible, while the convergence rate describes the ability of the optimizer to converge to the optimal solution with the minimum amount of evaluations as possible (modeFrontier, n.d.). Focusing on Building Performance Optimization (BPO), Nguyen et al. (2014) suggest a number of considerations, in order to select an optimization algorithm:

- Type of the optimization problem (static, dynamic, etc.)
- Type of the design variables (discrete, continuous, both)
- The possible constraint(s) applied at the set objective(s)
- Type of the objective function (linear or nonlinear, number of local minima, etc.)
- The availability of analytic first and second order derivatives of the objective(s)
- Performance of optimizers with similar aspects

The most commonly used algorithms in BPO studies can be categorized in three main groups: enumerative, deterministic and stochastic algorithms. The enumerative optimizers search for stationary points and as a result, they can converge to a local optimum at an early stage in the search process. They are also not suggested for wide solution spaces because they are computationally expensive algorithms. The deterministic algorithms are applied for optimization

problems with objective functions that have continuity and derivability. As a result, they are not suitable for discontinuous problems. Stochastic algorithms use randomness during the search process, they are able to avoid local optima and allow dealing also with a non-linear domain (Attia, Hamdy, Brien, & Carlucci, 2013).

Optimization problems dealing with building performances are usually nonlinear (Wetter & Wright, 2004), and that is the reason why stochastic algorithms, and especially genetic algorithms are used for most of the related studies. Weibel et al. (2019) compare the performance of different optimizers used in BPO problems, including randomized, deterministic and model-based algorithms, according to common metrics, such as robustness, stability, ranking and convergence rate. They conclude that no optimizer dominates the set benchmarks for all performance criteria; however, they rank them in terms of the set performance metrics (Waibel, Wortmann, Evins, & Carmeliet, 2019).

Last but not least, BPO is a complex problem, because of the non-linear, usually discrete characteristics, as well as the high number of variables. Therefore, it is considered difficult to reach the global optimum in an optimization problem of that kind. However, the optimization results can indicate well-performing designs, with much higher values of performance compared to non-optimized designs (Nguyen et al., 2014).

5.2. Optimization and design space exploration

The primary aim of the optimization is to find the optimum solution according to the objective(s) set for a specific problem. In addition to that function, a lot of researchers indicate the importance of the design exploration of the solution space. According to Turrin (2014), the great value of using the optimization as an exploration tool is, first of all, the knowledge gained by the designer during that process. In the post-processing phase, the designer can explore the relations between the inputs and the outputs, and also be informed about the performance of sub-optimal solutions. Secondly, in design related optimization problems, some criteria, such as soft issues, are not included in the optimization process, as they cannot be represented by numeric indicators. Therefore, design space exploration allows the designer to evaluate both optima and sub-optima, according to additional criteria.

Similarly, Wortmann and Schroepfer (2019) refer to the "performance-informed" design space exploration (DSE), which has a triple role: selection, refinement and understanding. More specifically, the exploration of the solution space allows the designer select among groups of design alternatives, based on their performance. The refinement allows the "customization" of the results, to some extent, by the designer. For example, the designer can modify a well-performing design suggested by the optimization, according to criteria not set in the automated process, such as soft criteria (aesthetics). Lastly, the design

space exploration gives insight to designers regarding the relation between the inputs and the outputs of the optimization, and also between the performance and the appearance of the design instances (Fig. 5.3).
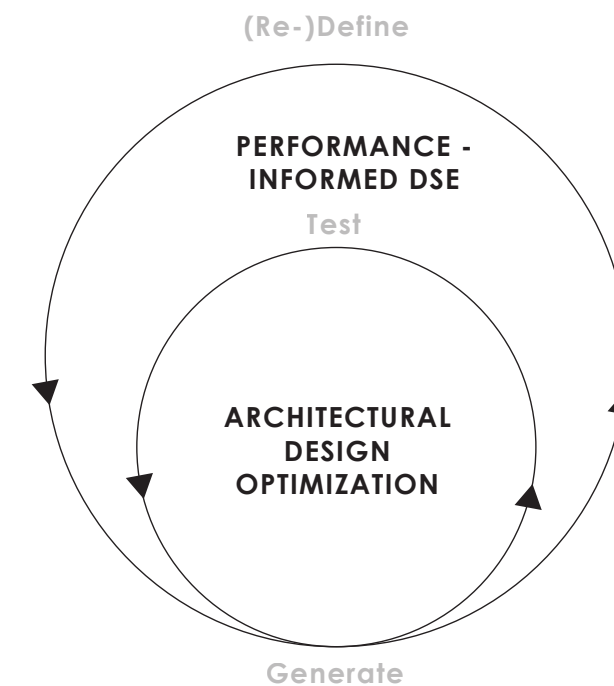

Figure 5.3: Integrated architectural design cycles (Wortmann & Schroepfer, 2019).

06
Optimization study

6. Optimization study

The aim of the research is to establish guidelines for the façade design of high-rise nZEBs (offices), in the temperate climate. The Rotterdam Science Tower in Rotterdam, the Netherlands, known also as the Marconi tower, is selected as a reference building for the study. That building is selected because it represents a typical office building in the Netherlands, regarding the shape of the building. It has also one of the most common office layouts, the open office layout.

Although the open office layout has been associated to lack of privacy and increased noise, it is noticed that many companies still prefer that layout, merely due to low cost in construction and maintenance (Brennan, Chugh, & Kline, 2002). For that research, the open office layout category includes different types, namely the "bull pen" office, the landscape office, the cubicles and the clusters, since they all refer to a unified space, without high partition walls (see Appendix 01). Apart from the application of that layout type in a general practice, a great advantage of the open office layout is that it can be modeled as only two thermal zones in the energy simulation programme, which reduces considerably the time for running the simulations.

For the simulations, Rhino 6 and Grasshopper 1.0.0007 (GH), developed by Robert McNeel & Associates are used. More specifically, the plug-in Honeybee (ver 0.0.64) is used for the energy and daylight simulations.

6.1. Reference building

6.1.1. Building description

The Rotterdam Science Tower, part of the Europoint Complex, in the Merwe-Vierhavens (M4H) area, in Rotterdam, is used as a reference building for the optimization study. The M4H area is part of the Rotterdam Makers District, a place which hosts entrepreneurs working on new technologies, such as digitization, robotization, 3d printing, sustainable energy and materials etc. The plan of the municipality and the port authority of Rotterdam is to establish the area as a place for experimentation, innovation and networking, based on new technologies and sustainable approaches. The area is a famous former shipyard with a lot of abandoned buildings, which can facilitate new businesses. The Europoint Complex located at the Marconiplein, stands out in the M4H district, as it consists of three identical 90-meter-high towers (Fig.6.2, 6.3). The Marconiplein is expected to be a vibrant, dense urban area, facilitating offices, housing and catering establishments (ROTTERDAM MAKERS DISTRICT, n.d.).

The Rotterdam Science Tower, the Europoint IV building, was designed by the renowned architectural firm, Skidmore Owings & Merrill (SOM), in 1978. The 21-storey building has an open-office layout and a centrally located core, which

which facilitates vertical circulation and building services. The columns are placed on the façade, leaving a free space inside without intermediate columns. The façade consists of travertine cladding and singe glazing windows, which are expected to perform insufficiently, regarding thermal insulation and water tightness (MOR, 2018).

The building is 33.01 x 47.41m and the core is 14.41 x 21.61m, in plan view. The façade frame consists of columns, with dimensions of 0.56 x 0.90m and beams of 0.56 x 0.65m. Secondary beams, made by prefabricated reinforced concrete, are clamped on the core and supported at the façade. These beams are arranged in a grid of 1.80m in parallel, and radially in the corners. Prefabricated slabs are used for the floor, while a thin layer of concrete cast-in-situ, keeps the secondary beams and the floor together (MOR, 2018).
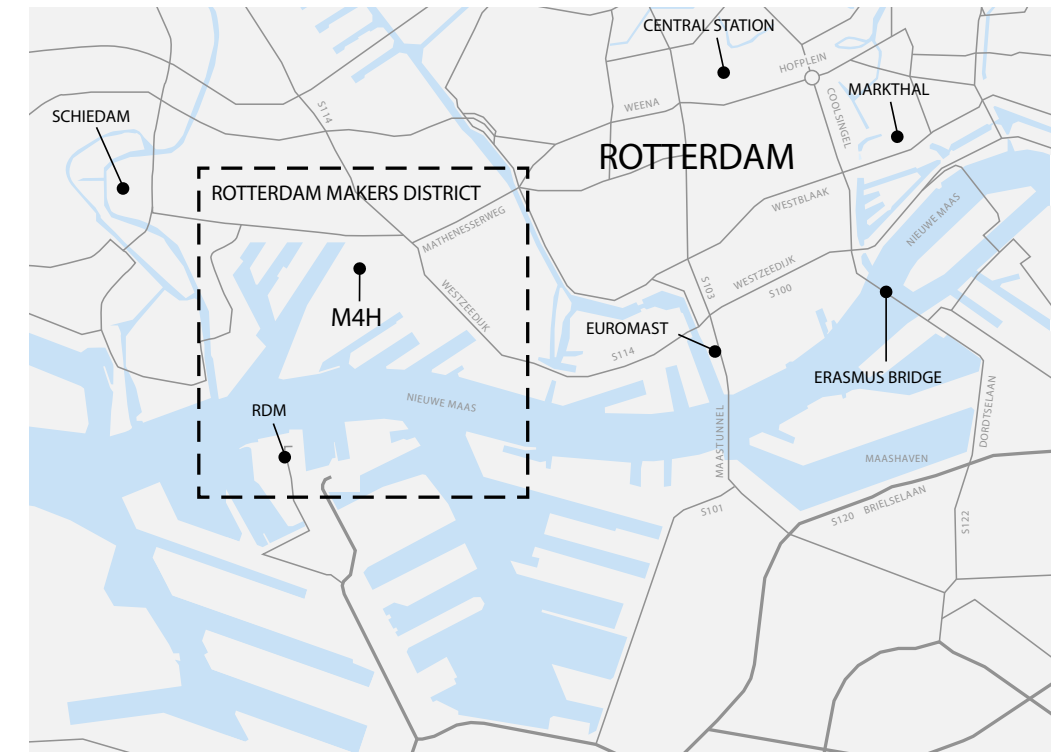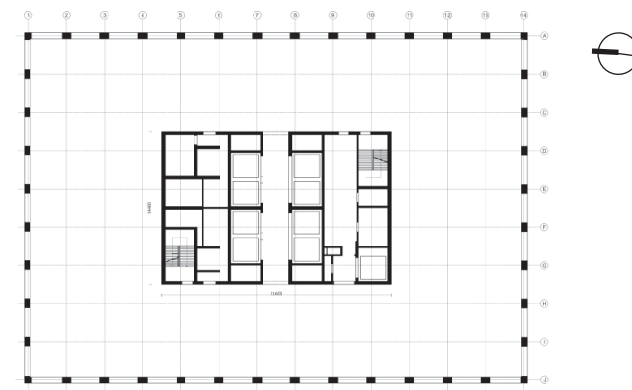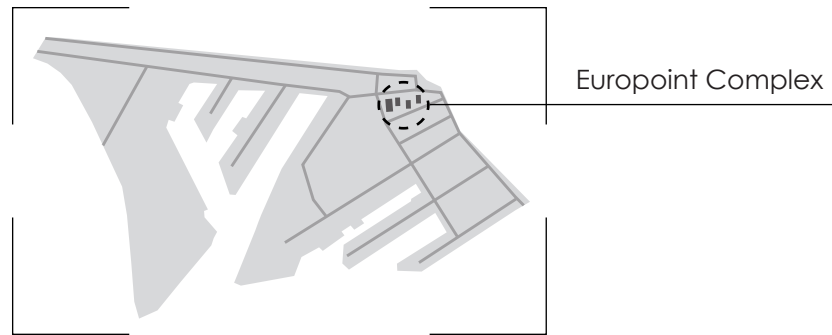

Figure 6.1: The Rotterdam Makers District area, the Netherlands. Adapted from: (ROTTERDAM MAKERS DISTRICT, n.d.)

Europoint Complex

Rotterdam Science Tower

Figure 6.2 (above): The Europoint Complex in the Merwe-Vierhavens (M4H) area.
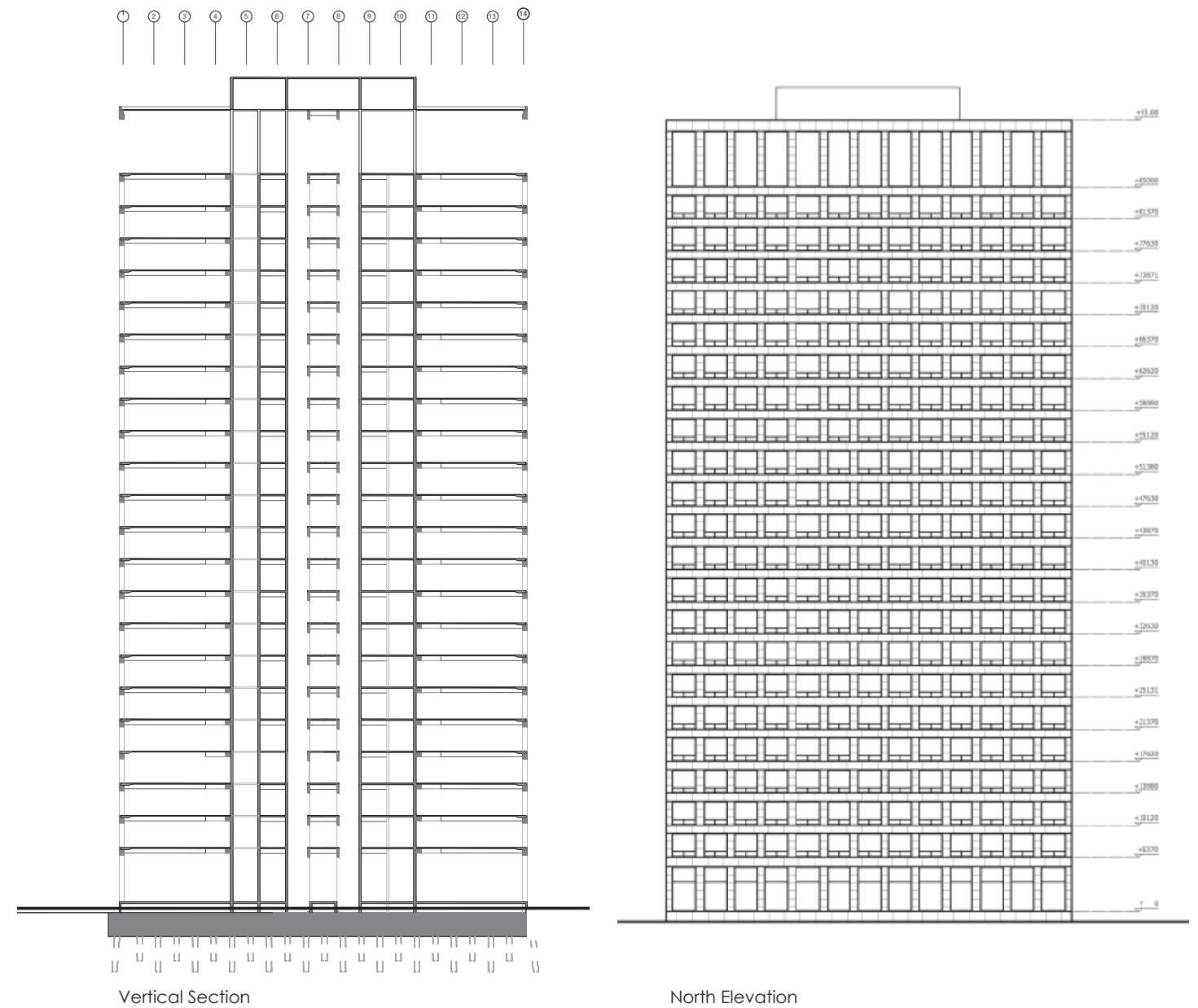Figure 6.3 (below): The Rotterdam Science Tower (ErasmusMC, 2015).

Typical Floor Plan

Vertical Section

North Elevation

Figure 6.4: Drawings of the Rotterdam Science Tower (MOR, 2018)

6.1.2. Analysis of the climate conditions

The climatic conditions of the city are analyzed, in order to understand different environmental aspects that affect the energy performance of the building. For that reason, data for the temperature, radiation and wind speed range are presented. The software Climate Consultant 6.0 is used for that analysis. The weather file for Amsterdam, retrieved from the EnergyPlus website (EnergyPlus, n.d.), is used for both the climate analysis and the simulations, as this is the closest location to Rotterdam with available weather data.

According to the Köppen climate classification, the climate of Amsterdam is characterized as oceanic (Cfb). The average temperature is 10^0C annually, and therefore, the climate is mostly considered as heating based. The warmest month is August, while the coldest month is February, with an average monthly temperature of 17^0C and 3^0C respectively (Fig.6.6). Regarding global horizontal radiation, the maximum radiation is reached in July (4934 Wh/m^2), and the minimum in December (463 Wh/m^2) (Fig.6.7). Additionally, the wind speed has higher values at winter, with a pick in January (7m/s). During summer, the average wind speed is 4m/s (Fig.6.8).

Figures from top to bottom:

Figure 6.6: Dry bulb temperature range graph, average monthly – Amsterdam weather file (exported from Climate Consultant 6.0)

Figure 6.7: Radiation range graph, average daily total – Amsterdam weather file (exported from Climate Consultant 6.0)

Figure 6.8: Wind velocity range graph – Amsterdam weather file (exported from Climate Consultant 6.0)
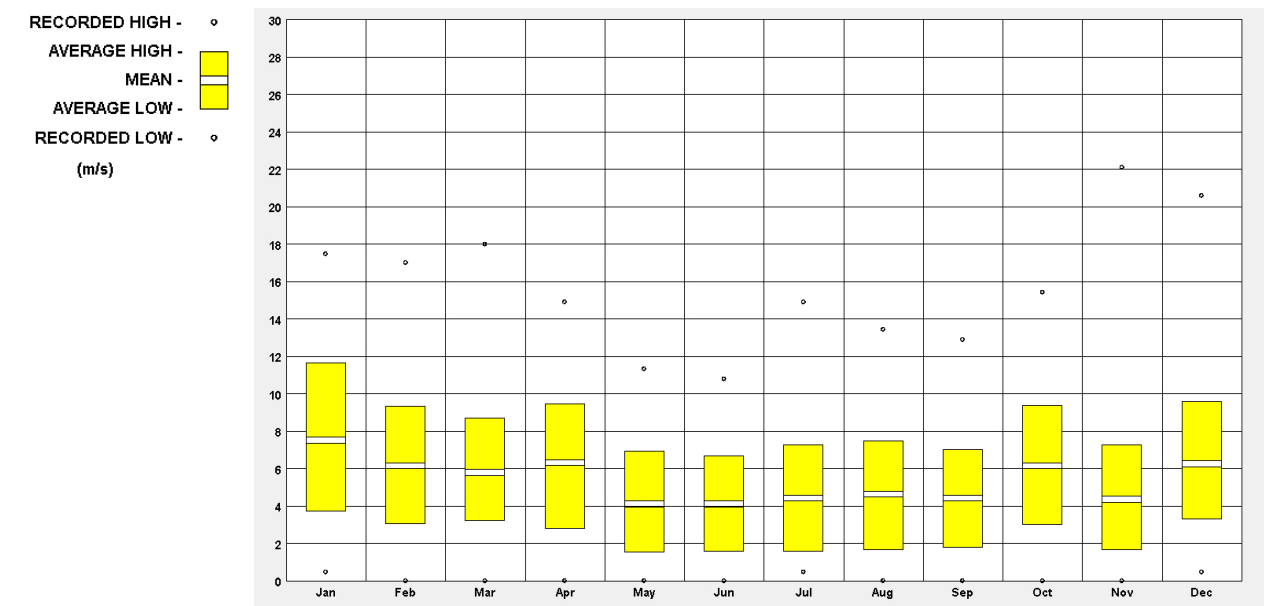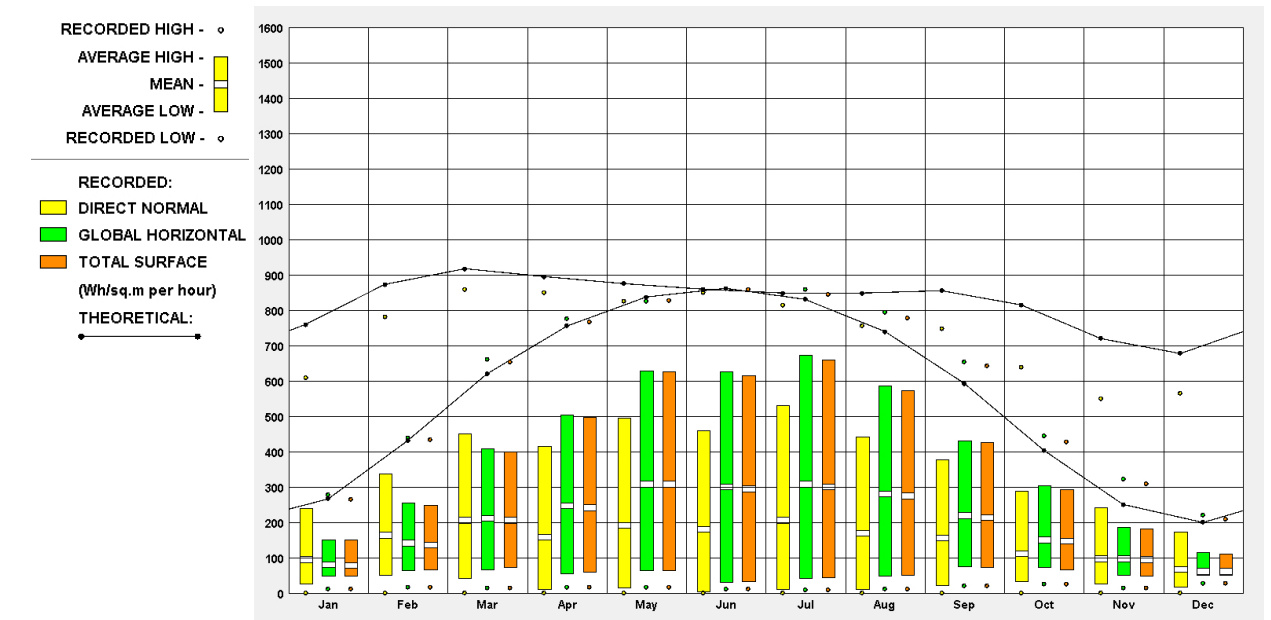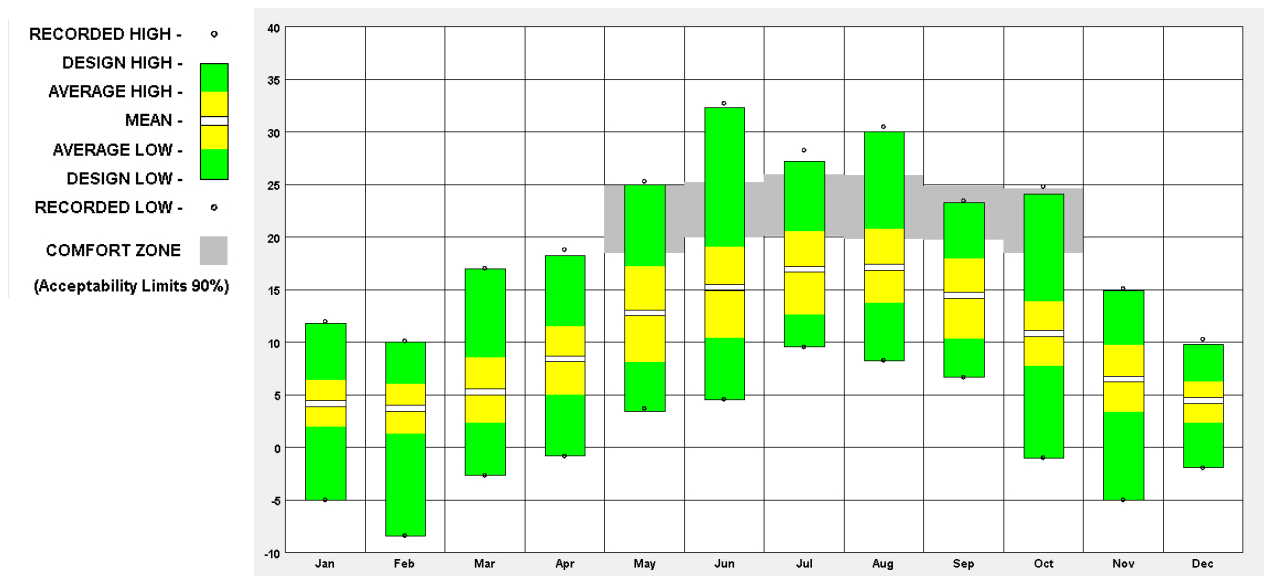
6.2. Energy simulation set-up

For the optimization process, three floors at different height are selected. Each floor consists of two thermal zones: the perimeter and the core (Fig. 6.9, 6.10). The existig building has a floor height of 3.75m, and that is adjusted to 3.6m, in order to be representative for offices in the Netherlands.

EnergyPlus takes into account the local climate conditions (outdoor air temperature and wind speed) for each zone, as a function of height above ground. The outdoor air temperature and the wind speed according to height are considered for the calculations regarding the infiltration and the ventilation (Big Ladder, 2014b) (see Appendix 01: Atmospheric properties according to building height).

6.2.1. Input data

The inputs used for the optimization are presented in Figure 6.11, and are analyzed in more detail in the following subchapters. The simulations run with a timestep of 6 per hour, and for an annual period analysis. As described before, for the simulations, the weather file for Amsterdam, retrieved from the EnergyPlus website (EnergyPlus, n.d.) is used, as this is the closest location to Rotterdam with available weather data.
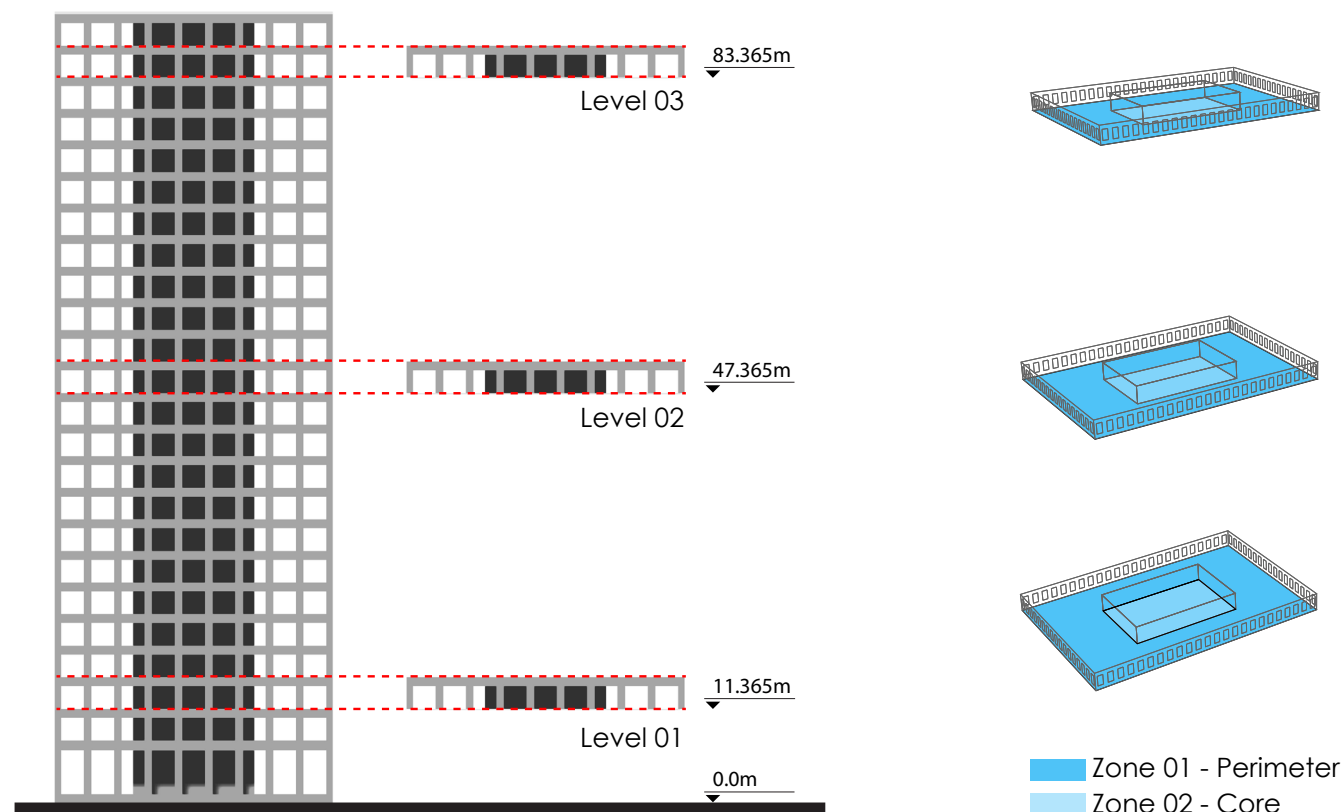

Figure 6.9 (left): The three floors, in different heights, to be tested.

Figure 6.10 (right): The geometry of each floor is divided in two thermal zones for the energy simulations.

	Honeybee
Construction	Outermost to innermost layer
Exterior wall conctruction	R-value: variable
Interior wall conctruction	1. Plaster (0.013m)/ 2.Concrete block (0.15m)/ 3. Plaster(0.013m) R-value= 0.515 m2-K/W
Internal floor/ceiling conctruction	1. Concrete reinforced (0.14m)/ 2. Screed(0.02m)/ R-value= 0.669 m2-K/W
Glazing construction	U-value: variable G-value: variable VT-value: variable
Airtightness	Zone 01: 0.137 (ac/h) - 24/7 Zone 02: 0 (ac/h) - 24/7
Activity	
Occupancy schedule	8.00-17.00 - 5 days
Occupancy density	0.111 people/m2
Metabolic rate	Zone 01: 123 (W/per person) Zone 02: 140 (W/per person)
Heating setpoint	21 ºC
Heating setback	16 ºC
Cooling setpoint	25 ºC
Cooling setback	30 ºC
Office equipment - Power density	Zone 01: 15 (W/m^2) Zone 02: 0 (W/m^2)
Lighting	
Power density	2.5 (W/m^2) - 100lux
Target Illuminance	Zone 01: 500 lux Zone 02: 200 lux
Lighting control	On
HVAC	
HVAC system	Fan Coil Units + DOAS
HVAC availability	all year - 5 days
Economiser (type)	Differential dry bulb
Outside air definition method (Mechanical ventilation)	Sum(per person + per area + per zone + ac/h)
Natural Ventilation Outdoor tempera-tures limits	On Min. temperature: 21ºC Max.temperature: 25ºC

Figure 6.11: Input data used for the simulations in Honeybee.

6.2.2. Variables for the optimization

For the window to wall ratio, six values are tested for the optimization process: 30%, 40%, 50%, 60%, 70% and 80%. Every façade orientation and every floor level has different window to wall ratio. A higher ratio is expected to increase the solar gains and daylight, but also the heat loss during winter.

Regarding the wall R-value, the values that are tested are the following: 4.5, 5.5, 6.5 and 7.5 m²-K/W. According to the Nedelands Vlaamse Bouwfysica Vereniging (2016), R-values for the closed part of the facades with a value between 4.5 and 5.0 m²-K/W are classified as "Basic", between 5.0 and 6.5 m²-K/W are ranked as "Good", while those with a values higher than 6.5 m²-K/W are reported as "Excellent" (Table 2.4).

For that research, the U-value of the glazing part takes into account the properties of both the glass and the frame. The values to be tested are the following: 0.80, 1.20, 1.60 W/m²-K, which are selected according to the Nedelands Vlaamse Bouwfysica Vereniging (2016): U-values between 1.65 and 1.20 W/m²-K are reported as "Basic", values between 1.20 and 0.80 W/m²-K are reported as "Good", and those with a value lower than 0.80 W/m²-K are classified as "Excellent". The value of 0.80 W/m²-K refers to a triple glazing, the value of 1.20 W/m²-K refers to a double glazing, while the 1.60 W/m²-K value refers to a double glazing with a worse insulation performance. Since the building uses a mixed-mode ventilation system, the insulation properties of the facade, closed part and glazing, are only relevant when the building runs on mechanical ventilation.

Regarding the g-value of the glazing, the values that are tested are: 0.3, 0.4 and 0.5. The lower g-values allow less solar gain into the building, and therefore will minimize the cooling load, but maximize the heating load.

For the visible light transmittance (VT) of the glazing, the following values are taken into account for the optimization process: 0.5, 0.6 and 0.7. Higher values will allow more natural light in the building, and as a result minimize the lighting demand, which is expected to be high for offices.

6.2.3. Building orientation and shape

In order to be able to define guidelines, more cases, regarding the shape and the orientation of the building, should be tested. The rectangular (shape 1) and the square floor plan (shape 2) are tested, as these are typical shapes for offices in the Netherlands. Also, although the floor height in the Marconi tower is 3.75m, it is adjusted to 3.6m, as this is a common value for that kind of buildings. The alternatives that are tested are presented on Figure 6.13. The square floor plan has the same surface area as the rectangular one (1.565m²).
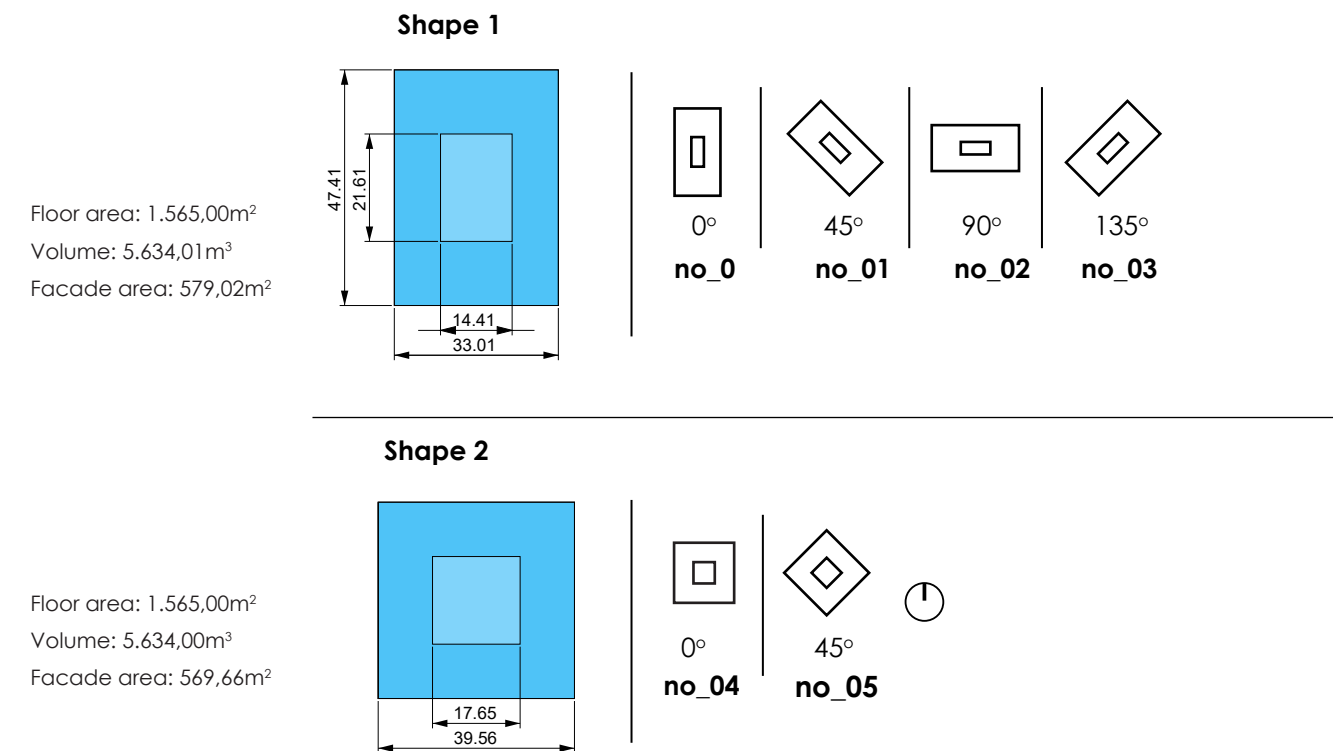

Shape 1

Floor area: 1.565,00m²
Volume: 5.634,01m³
Facade area: 579,02m²

0° no_0   45° no_01   90° no_02   135° no_03

Shape 2

Floor area: 1.565,00m²
Volume: 5.634,00m³
Facade area: 569,66m²

0° no_04   45° no_05

Figure 6.13: Tested geometries for the optimization

w/w (per facade and per floor)	[30 / 40 / 50 / 60 / 70 / 80] %
R-value ext.wall	[4.5 / 5.5 / 6.5 / 7.5] m²K/W
U-value glazing and frame	[0.8 / 1.2 / 1.6] W/m²K
g-value glazing	[0.3 / 0.4 / 0.5]
VT glazing	[0.5 / 0.6 / 0.7]

Figure 6.12: The variables to be tested for the optimization.

Regarding the definition in GH, at first, the dimensions of the building (exterior dimensions) and the dimensions of the core are defined, in order to create the floor of the tested geometry. That creates the base of the two thermal zones, the core and the perimeter. That surface is extruded in the Z-axis (building height), and then the surfaces representing the walls (exterior and interior walls), as well as the ceilings are separated based on orientation. The materials presented in Figure 6.11 are assigned to the surfaces, based on type (exterior wall/ceiling/floor etc). Also, the boundary condition (outdoors/adiabatic) of each surface is determined (Fig.6.14). After that, the surfaces are organized in two groups, in order to create the two thermal zones. Each thermal zone should create a closed Brep, consisting of a floor, a ceiling and (interior/exterior) walls.

The surfaces of the exterior walls are used in order to create the windows, based on the determined w/w ratio and the ceiling height. Then, the building programme of each thermal zone is defined: the building programme of zone_01 is "Office: OpenOffice" and of zone_02 is "Office: Corridor". Last but not least, the adjacency between the two zones is "found", so that the heat transfer between the adjacent surfaces is taken into account in the energy simulation (Fig.6.15).
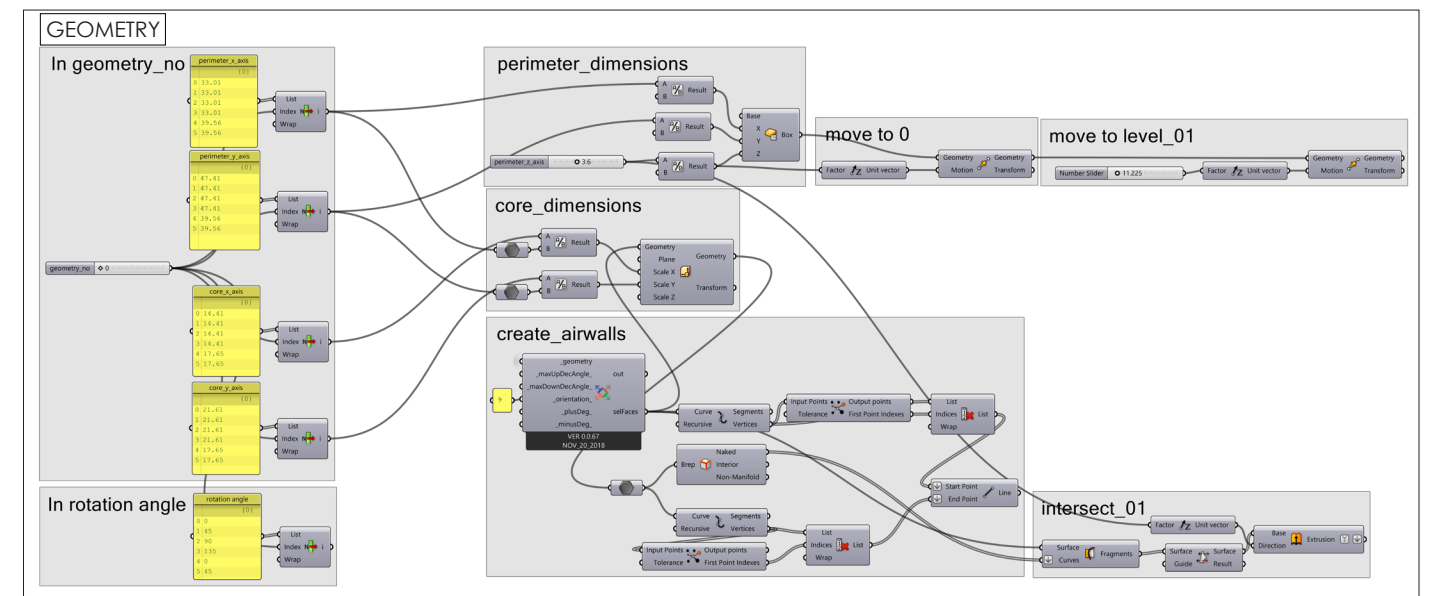
Figure 6.14: Definition in GH for creating the basic geometry: exterior walls, floors, ceilings and interior walls.
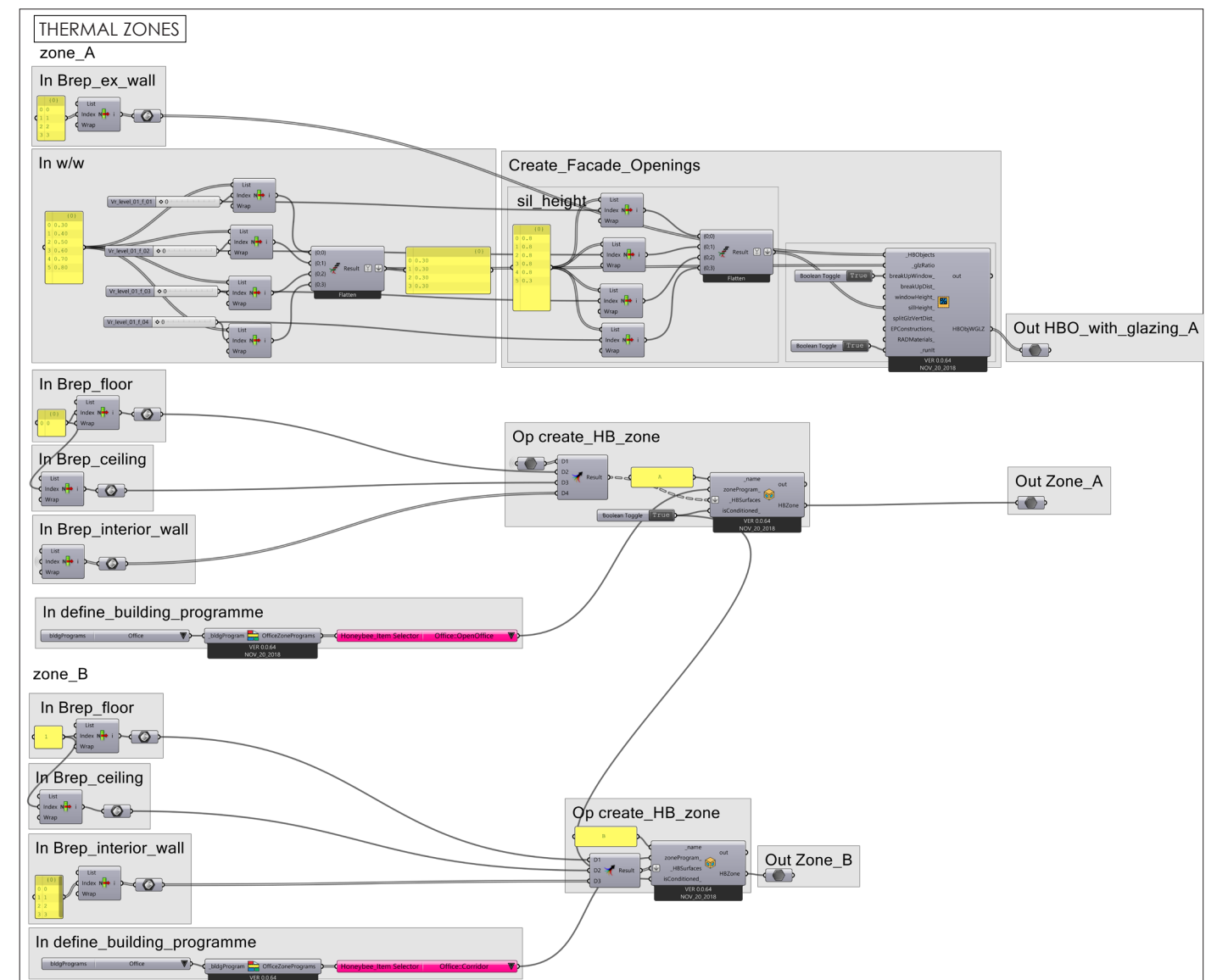

Figure 6.15: Definition in GH for creating the thermal zones.

6.2.4. Materials

Customized materials are created and assigned to each surface: internal floors, interior walls, exterior walls and glazing. The construction of the internal floor (similar to the ceiling) consists of the following layers: 1. Concrete reinforced (0.14m)/ 2. Screed (0.02m). The R-value of the floor is calculated to 0.669 m^2-K/W. The interior walls consist of the following layers: 1. Plaster (0.013m)/ 2.Concrete block (0.15m)/ 3. Plaster(0.013m). The R-value of that construction is 0.515 m^2-K/W. On the contrary, the construction of the exterior wall is simplified and represented only by the thermal resistance R-value, which serves as a variable for the optimization.That method neglects the thermal mass of the assembly. However, the accuracy of the simulation results are expected to be acceptable, since lightweight constructions, with low mass, are commonly used for the facades of high-rise buildings. It should be noted that there are no ceilings, in order to take advantage of the thermal mass of the floors (exposed concrete). Thermal mass is also provided by the internal walls. Lastly, the construction of the glazing (glass and framing) is represented by three values: the U-value, the g value and the VT, which are all variables for the optimization (Fig.6.16).
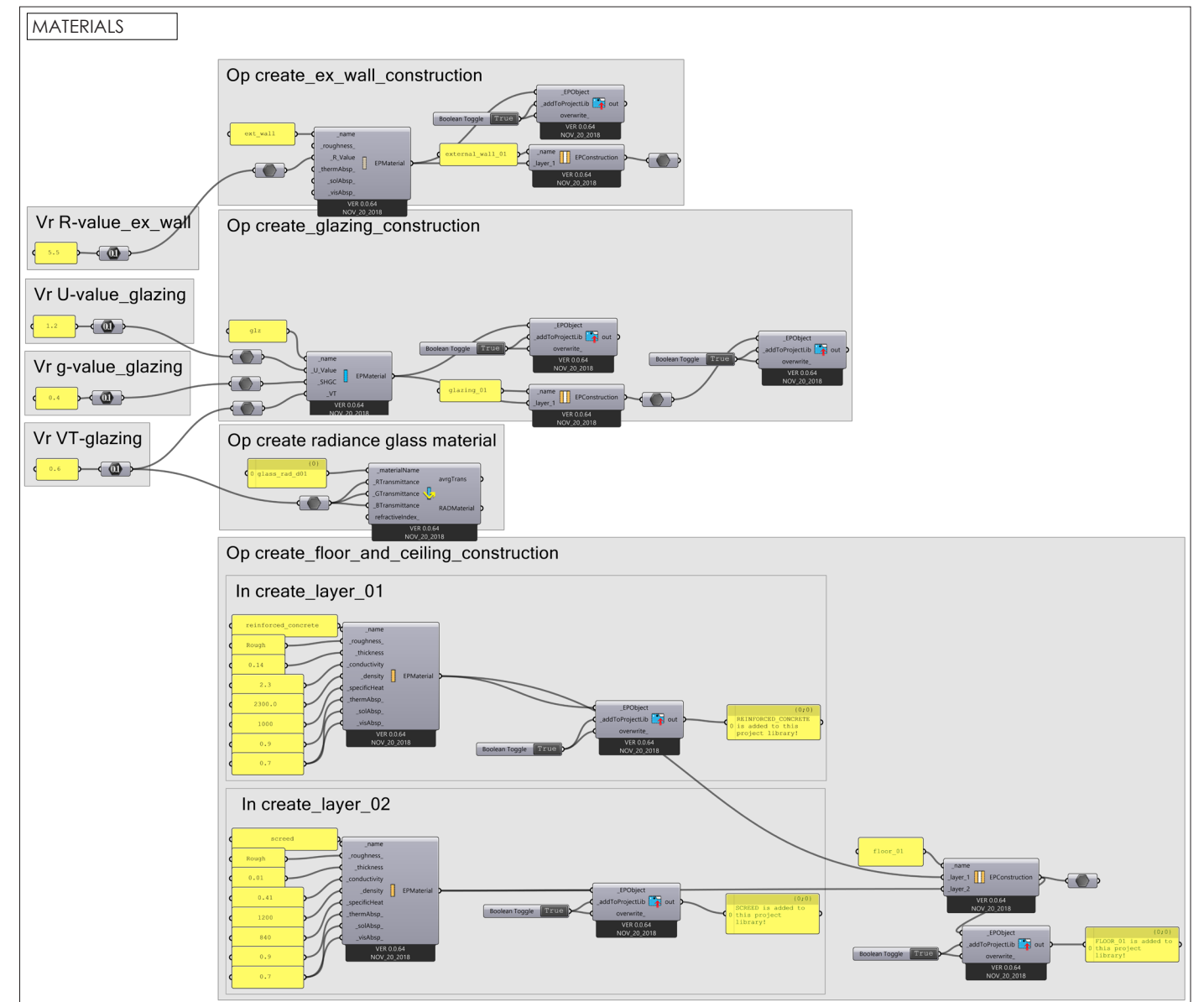

Figure 6.16: Definition in GH for creating the materials.

6.2.5. Internal loads

The values for the ventilation per area, the ventilation per person and the infiltration rate per area are according to the Nedelands Vlaamse Bouwfysica Vereniging (2016) (Table 2.5 and 2.6). The assigned equipment load per area is 15W/m² and 0W/m² for zone_01 and zone_02 respectively, while the number of people per area is determined to 0.111, as this is a common value for offices. The lighting density per area is 12.5W/m² and 5W/m² for zone_01 and zone_02 respectively, corresponding to a lighting power of 2.5W/m² per 100 lux (LED) (Fig.6.17).

6.2.6. Schedule

The occupancy schedule that is used for the optimization is the following (Fig.6.19):

Monday-Friday: 8.00 – 17.00

The equipment schedule follows the occupancy schedule. The lighting schedule for zone_01 is determined by the daylight simulation: when daylight is not sufficient to reach the illuminance threshold (500 lux), then the lighting is switched on. In that way, there is a considerable saving in the lighting demand, considering that lighting is one of the highest expected energy loads for an office building. On the contrary, zone_02 does not have any access to natural light, and for that reason, the lighting schedule follows the occupancy schedule (Fig.6.18).
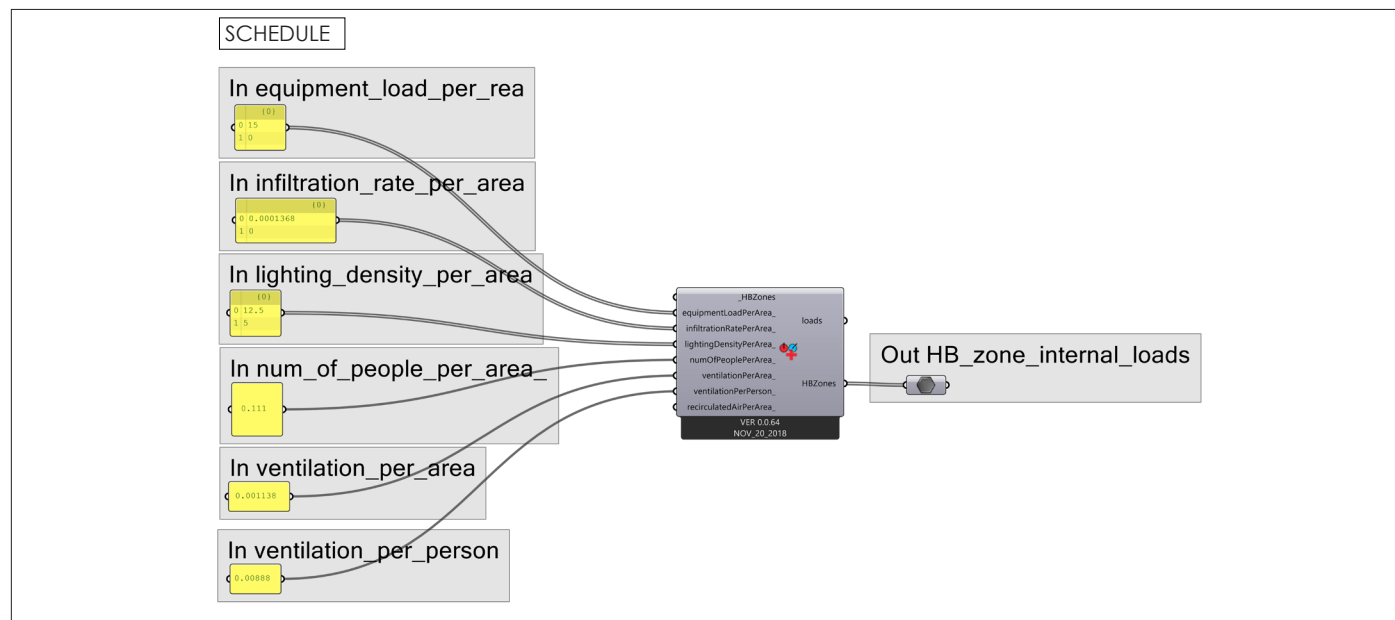

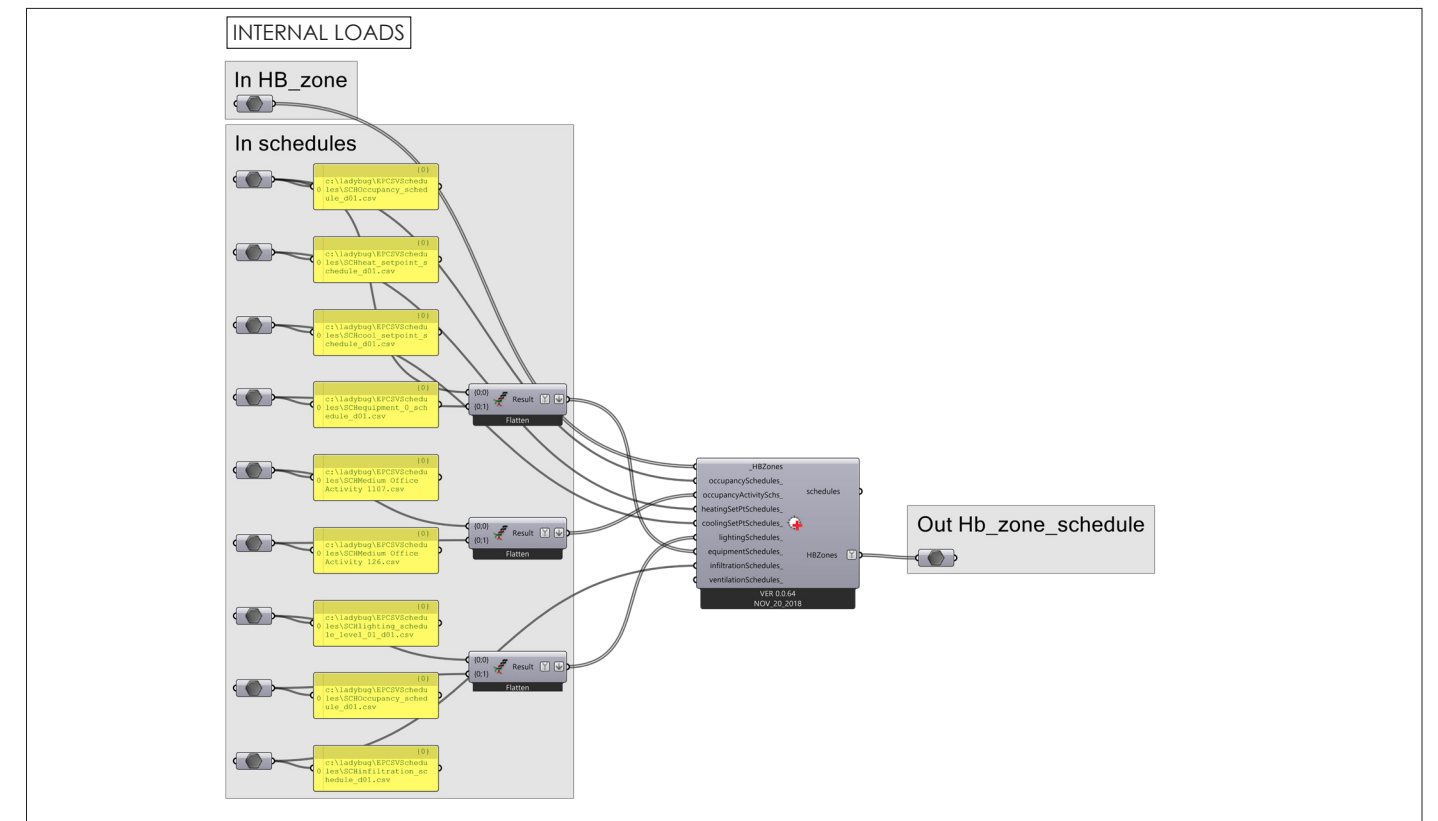Figure 6.17: Definition in GH for assigning internal loads.

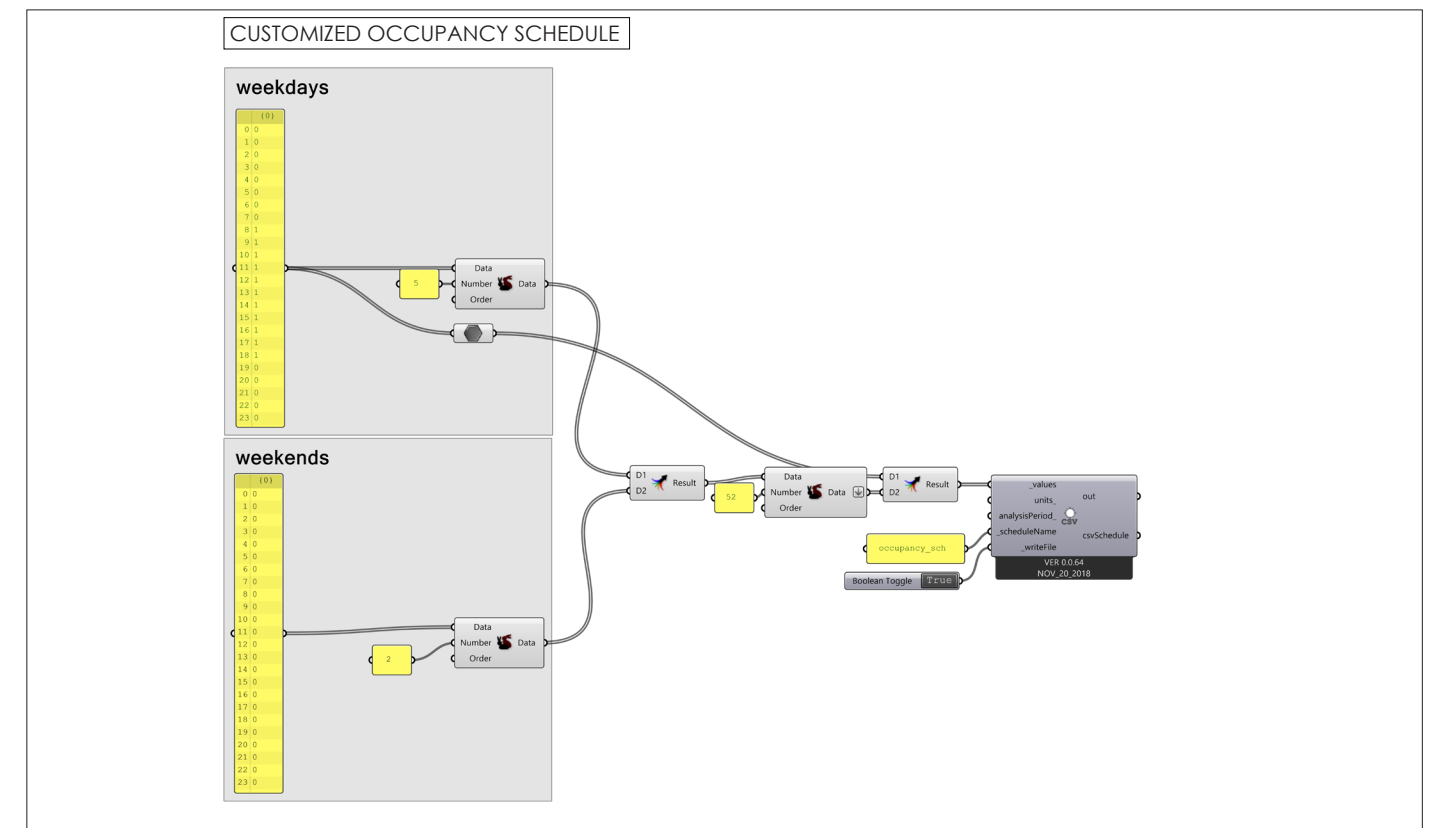Figure 6.18: Definition in GH for assigning schedules.

Figure 6.19: Definition in GH for creating a customized occupancy schedule.

6.2.7. Daylight simulation

For the daylight simulation, only zone_01 is considered, as zone_02 does not have any windows. The surface of the floor is divided in four areas, based on orientation, and a sensor is located in the middle of theses subsurfaces, 0.8m above ground level. The sensors measure the illuminance levels and control the lighting system accordingly, as described above (Fig.6.20). Since the daylight simulations are highly time-consuming, only one sensor point per orientation is used for the research. More sensor points would increase considerably the time needed per simulation. However, since no urban context and no shading devices are used for the study, using only one point as representative of each space is considered to be an accepted convention.

6.2.8. Natural ventilation

In order to minimize the cooling load, a natural ventilation strategy is followed, alongside to the mechanical ventilation. Wind driven cross ventilation is applied, since there are operable windows in all four facades. The operable part of each window is determined to be the 30% of the window area. Natural ventilation takes place when the outdoor temperature is between 21 and 25°C, since these are the heating and cooling setpoints (Fig.6.21).
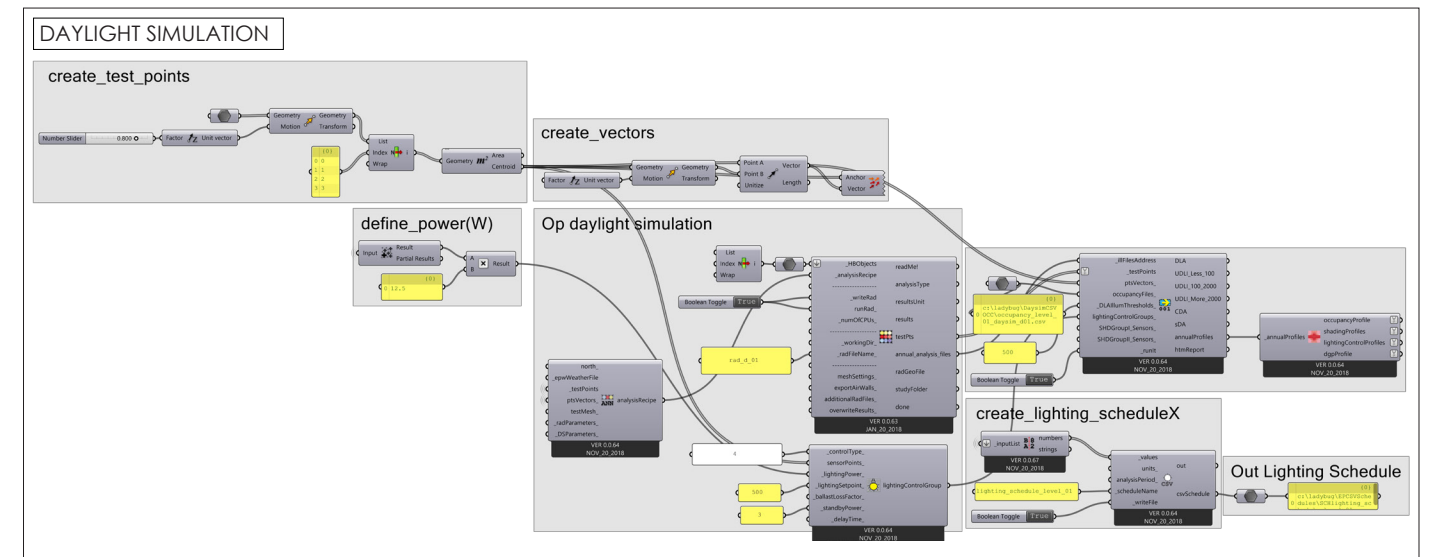

Figure 6.20: Definition in GH for the daylight simulation. The output of the operation is the lighting schedule for the specific zone.
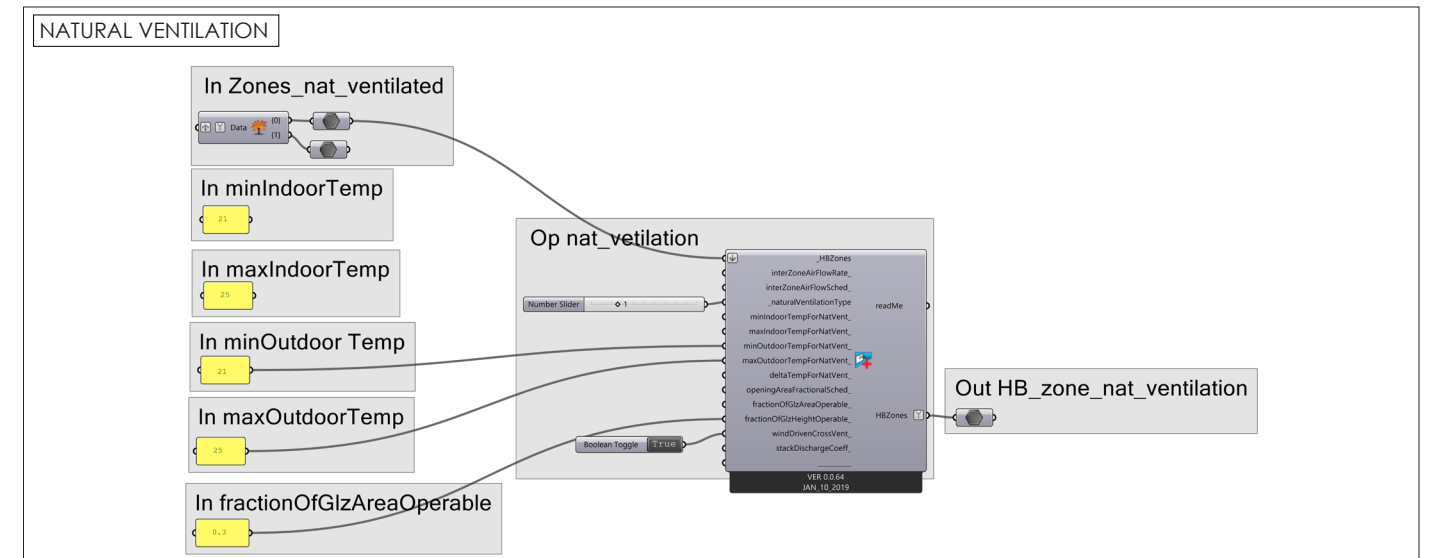

Figure 6.21: Definition in GH for assigning natural ventilation in Zone_A (perimeter).

6.2.9. HVAC

For the HVAC system, the fan coil unit with a dedicated outdoor air system (DOAS) is used, as it is a common system for offices. The HVAC availability schedule follows the occupancy schedule. A differential dry bulb air side economizer is set, in order to minimize the cooling load, and sensible heat recovery is used, with an efficiency of 80%. The cooling setpoint and setback temperatures are 25 and 30 °C respectively, while the heating setpoint and setback temperatures are 21 and 16 °C respectively. The daylight illuminance setpoints are 500 lux for zone_01 and 200 lux for zone_02 (Fig.6.22, 6.23).
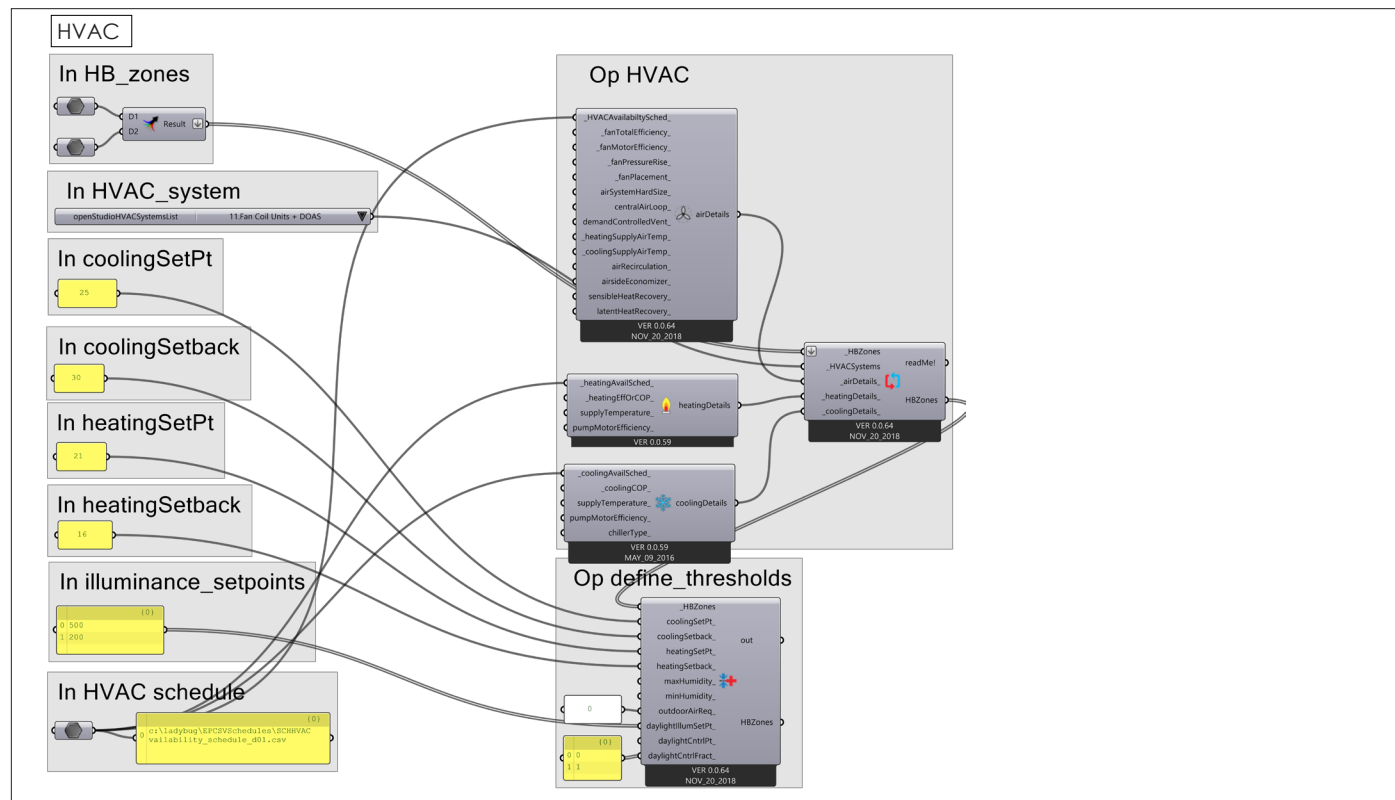

Figure 6.22: Definition in GH for assigning a HVAC system to zones. The thresholds for the simulation are also determined here.
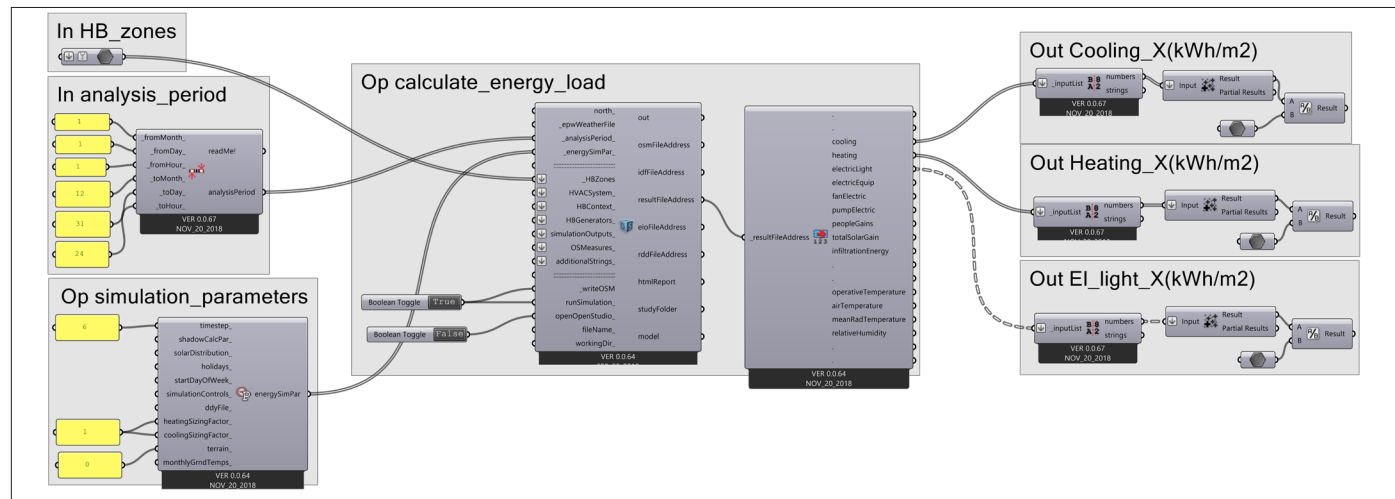

Figure 6.23: Definition in GH for the calculation of the energy load per floor.

6.2.10. Energy generation

The non-glazing surface of the exterior walls is used in order to produce energy. For that reason, BIPV panels are installed at the vertical surfaces of the walls in all four orientations. A product from the market is selected: polycrystalline high power solar cells (solarwatt, n.d.), with an efficiency of 16% (see Appendix 01, Fig. a.01.1 and Fig. a.01.2).

The formula used to calculate the energy generated is the following (photovoltaic-software, 2019):

$$E = A*r*H*PR \qquad (eq.6.1)$$

E = energy generated (kWh)

A = total PV panel area (m2)

r = solar panel yield or efficiency(%)

H = annual average solar radiation on tilted panels

PR = performance ratio, coefficient for losses

The performance ratio includes all losses of the system and for that case is calculated to be 0.85. The annual solar radiation captured by the panels is calculated with the Ladybug component: Ladybug_Radiation Analysis. For the calculation of the radiation, the annual period analysis, the epw file of Amsterdam and a grid size of 0.25m are used (Fig.6.24).
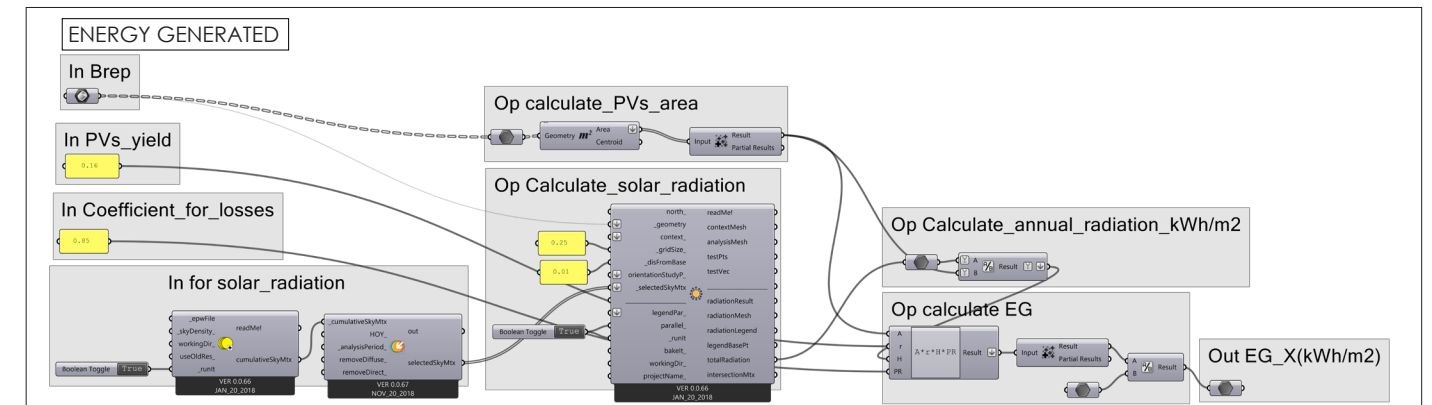

Figure 6.24: Definition in GH for the calculation of the energy generated per floor.

6.2.11. Thermal comfort

The building uses a mixed-mode ventilation strategy, and therefore the adaptive thermal comfort model is used, that follows the EN-15251 standards. An annual period analysis is used for the calculation of the thermal comfort of the occupants. The component outputs the percentage of time, through the year, that people are satisfied, as a string of 0's and 1's. From that list, only the time that the space is occupied is used in order to calculate the percentage of people satisfied (Fig.6.25).

6.2.12. Outputs and objective

The outputs of the optimization are the energy demand (kWh/m^2), the energy generated (kWh/m^2) and the thermal comfort (%), by floor and as total (mean value). The energy demand is the sum of the heating, cooling and lighting load. What is more, it is considered helpful for designers to have information about the breakdown of the energy demand and as a result, the heating, cooling and lighting load per floor, and the mean values(kWh/m^2) of them are included in the outputs.

The energy demand and the energy generated, as total values, are used to formulate the objective of the optimization. More specifically, the objective is to minimize the mean value of the energy demand subtracting the energy generated (kWh/m^2) (Fig. 6.26 and 6.27).

6.2.13. Constraint

The value of 90% of people satisfied is considered as a constraint for the optimization, following the new adaptive thermal comfort guidelines (Boerstra et al., 2015). Therefore, only the designs with thermal comfort more than 90% are considered for the design exploration.
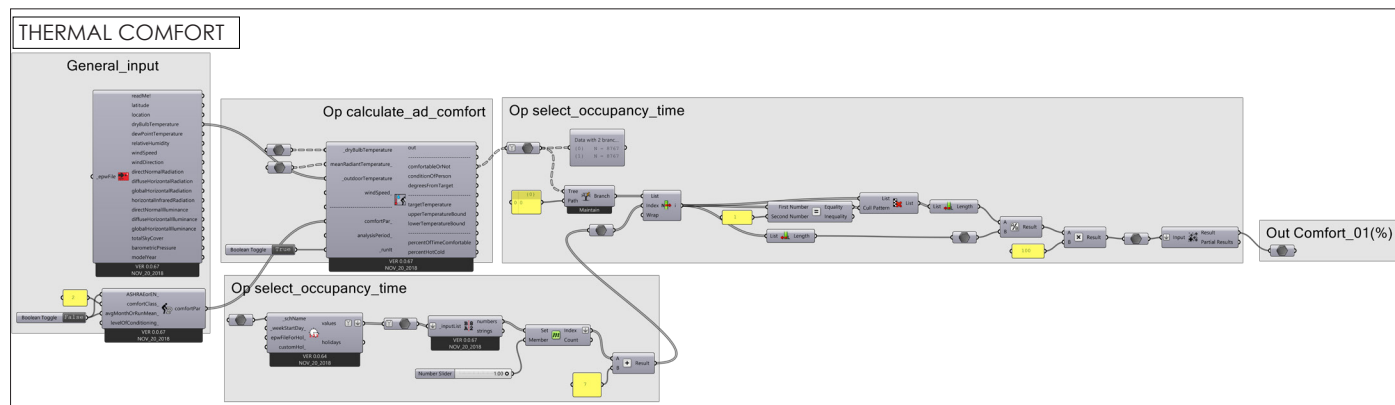

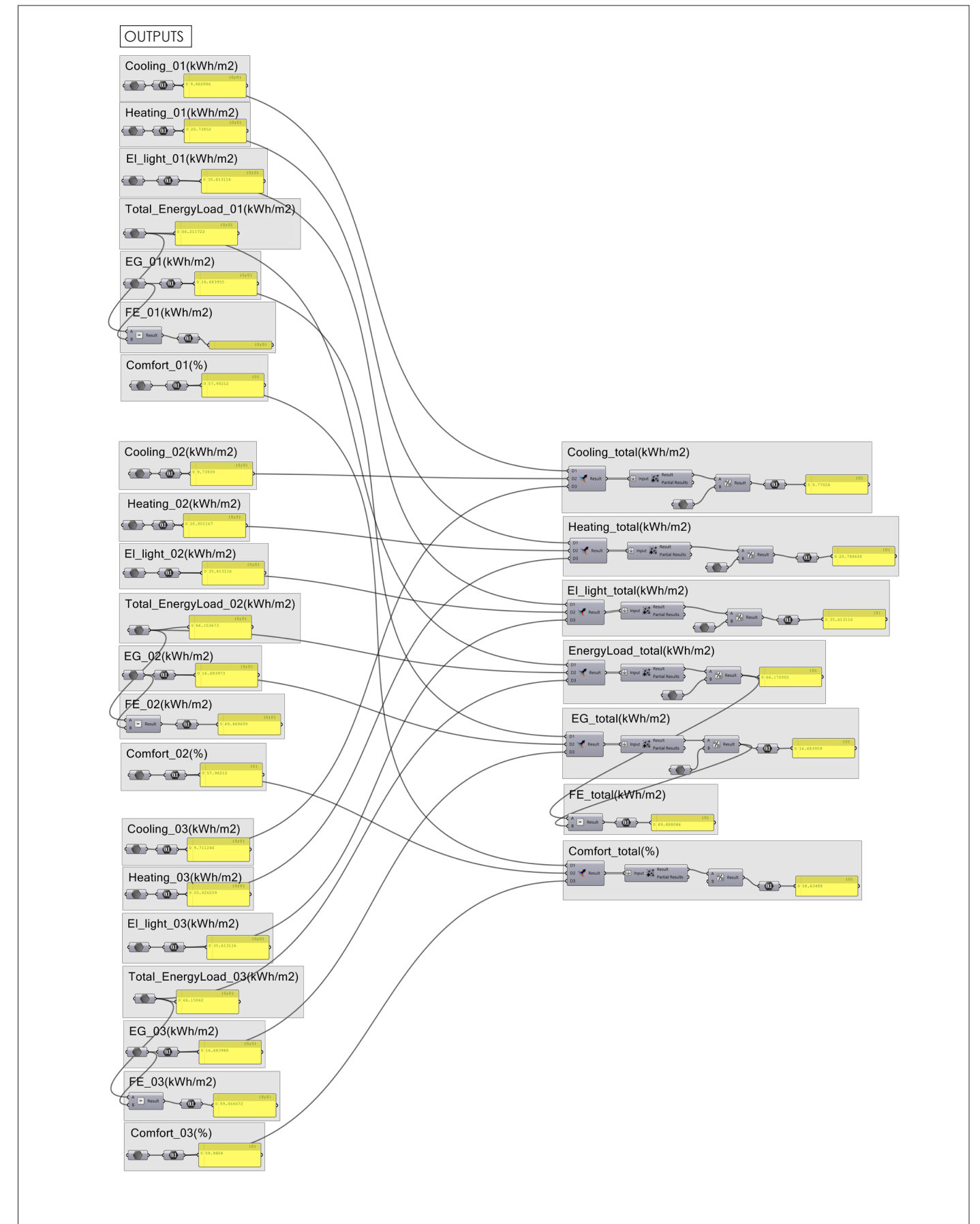Figure 6.25: Definition in GH for the calculation of the thermal comfort per floor.

Figure 6.26: Definition in GH showing how the outputs are organized.

Outputs

Per floor and total (average value):
Heating load (kWh/m²)
Cooling load (kWh/m²)
Lighting load (kWh/m²)
PV energy generated (kWh/m²)
Thermal comfort (%/occupancy time)

Objective

Min. (Energy demand total) - (PV energy generated total) (kWh/m²)

Energy demand total = **Heating load total + Cooling load total + Lighting load total** (kWh/m²)

Constraint

Thermal comfort > 90%

Figure 6.27: The outputs, the objective and the constraint of the optimization study.

6.2.14. Evaluation of developed workflow

During the time the thesis is conducted, Honeybee (HB) tools are under development, and therefore, the accuracy of the results obtained from the suggested workflow should be evaluated. For that reason, the simulation model in HB is calibrated according to DB, and the results of the energy simulations collected by the two programmes are compared. For the comparison, DesignBuilder v5.5.2.7., and Honeybee ver 0.0.64 are used. DesignBuilder (DB) is a well-established simulation software programme that provides performance analysis, including energy, comfort, HVAC and daylighting. It uses the EnergyPlus engine, as Honeybee.

For the comparative analysis, two designs with different glazing types (design 01 and design 02) are tested in both programmes. The inputs used in DesignBuilder are the same as those in HB (Table 6.2). For the HVAC system, the ideal air load system is used for both software programmes. That system adds or removes heat to the zone at 100% efficiency, and does not take into account the coefficient of performance (COP), as other typical HVAC systems (Big Ladder, 2014c).

The two software programmes show a similar trend regarding the energy performance of the two tested designs. For example, both programmes indicate that design 01 performs worst than design 02 reagrding the cooling load, but better regarding the lighting load (Fig. 6.28). However, there is a small difference in the numeric values between the two programmes.

One reason for that can be the different settings, in order to define the required parameters, during the calibration of the simulation models. For example, in DB the user defines the air tightness of the construction (ac/h), and also the fresh air (l/s/person) and the mechanical ventilation per area (l/s/m2), while in HB, one can control these parameters through the zone loads: infiltration rate per area (m³/s/m² floor area), ventilation per area (m³/s/m² floor area) and ventilation per person (m³/s/person). Also, HB does not offer the same freedom to users to control some parameters, as in DB, but instead, it has some predetermined values for some options. For example, one cannot control the fan pressure rise and the fan efficiency in the ideal air load system. However, the difference in the simulation results is acceptable, considering that the aim of the research is a comparative study between design alternatives, in early design stages. Therefore, in that context, the accuracy of the results obtained from the workflow in HB can be considered sufficient.
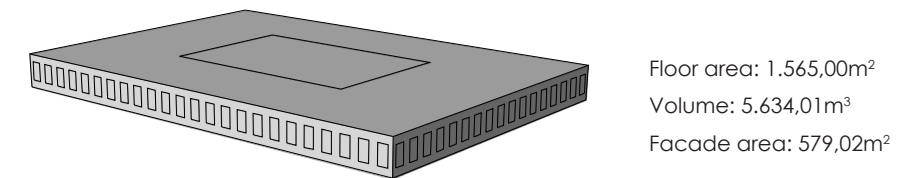
Floor area: 1.565,00m²
Volume: 5.634,01m³
Facade area: 579,02m²

Figure 6.28: Tested design for the comparative analysis between the two software programmes.

ID	Cooling demand (kWh)	Heating demand (kWh)	Lighting demand (kWh)	Equipment demand (kWh)	Total demand (kWh)
DB_01	3,271	1,661	19,918	41,564	66,414
DB_02	2,794	1,444	21,271	41,564	67,074
GH_01	3,525	1,964	17,707	44,183	67,380
GH_02	3,039	1,828	19,096	44,183	68,147

Table 6.2: Comparison of the simulation results between the two software programmes.

	DesignBuilder	Honeybee
Construction	Outermost to innermost layer	
Exterior wall conctruction	1. Brickwork outer (0.0450m)/ 2. XPS extruded polysterine (0.15m)/ 3.Concrete block (0.1050m)/ 4. Gypsum plastering (0.015m) R value= 6.421 m2-K/W	1. Brickwork outer (0.0450m)/ 2. XPS extruded polysterine (0.15m)/ 3.Concrete block (0.1050m)/ 4. Gypsum plastering (0.015m) R value= 6.421 m2-K/W
Interior wall conctruction	1. Plaster (0.013m)/ 2.Concrete block (0.15m)/ 3. Plaster(0.013m) R value= 0.515 m2-K/W	1. Plaster (0.013m)/ 2.Concrete block (0.15m)/ 3. Plaster(0.013m) R value= 0.515 m2-K/W
Internal floor/ceiling conctruction	1. Concrete reinforced (0.14m)/ 2. Screed(0.02m) R-value= 0.669 m2-K/W	1. Concrete reinforced (0.14m)/ 2. Screed(0.02m) R-value= 0.669 m2-K/W
Design 01 - Glazing type	Dbl LowE (e2=.2) Clr 6mm/13mm Arg: g value=0.635/ VT value= 0.721/ U value=1.689 W/m2-K	Dbl LowE (e2=.2) Clr 6mm/13mm Arg: g value=0.635/ VT value= 0.721/ U value=1.689 W/m2-K
Design 02 - Glazing type	Trp LowE Film (77) Clr 3mm/13mm Air: g value=0.469/ VT value= 0.637/ U value=1.244 W/m2-K	Trp LowE Film (77) Clr 3mm/13mm Air: g value=0.469/ VT value= 0.637/ U value=1.244 W/m2-K
Airtightness	Zone 01: 0.137 (ac/h) - 24/7 Zone 02: 0 (ac/h) - 24/7	Zone 01: 0.137 (ac/h) - 24/7 Zone 02: 0 (ac/h) - 24/7
Activity		
Occupancy schedule	8.00-17.00 - 5 days	8.00-17.00 - 5 days
Occupancy density	0.111 people/m2	0.111 people/m2
Metabolic rate	Zone 01: 123 (W/per person) Zone 02: 140 (W/per person)	Zone 01: 123 (W/per person) Zone 02: 140 (W/per person)
Heating setpoint	21 ºC	21 ºC
Heating setback	16 ºC	16 ºC
Cooling setpoint	25 ºC	25 ºC
Cooling setback	30 ºC	30 ºC
Office equipment - Power density	Zone 01: 15 (W/m2) Zone 02: 0 (W/m2)	Zone 01: 15 (W/m2) Zone 02: 0 (W/m2)
Lighting		
Power density	2.5 (W/m2) - 100lux	2.5 (W/m2) - 100lux
Target Illuminance	Zone 01: 500 lux Zone 02: 200 lux	Zone 01: 500 lux Zone 02: 200 lux
Lighting control	On	On
HVAC		
HVAC system	VAV dual duct air cooled chiller (ideal air loads)	Ideal air loads
HVAC availability	all year - 5 days	all year - 5 days
Heat recovery effectiveness	0.8 - sensible heat	0.8 - sensible heat
Economiser (type)	Differential dry bulb	Differential dry bulb
Outside air definition method (Mechanical ventilation)	Sum(per person + per area)	Sum(per person + per area) + per zone + ac/h)
Natural Ventilation Outdoor temperatures limits	On Min. temperature: 21ºC Max.temperature: 25ºC	On Min. temperature: 21ºC Max.temperature: 25ºC

Table 6.3: The inputs used for the simulations in DB and HB.

6.3. Optimization

For the optimization, the software ModeFRONTIER 2018R3 (MF) is used. Figure 6.29 presents the developed workflow regarding the connection between GH and MF. It is a coupling loop that continues until the objective function that has been set is met.

There are three basic steps that are followed in the optimization process in MF: the workflow set-up, the analysis run and the design exploration of the solution space. During the workflow set-up, the properties of the inputs, the outputs, the objectives and the constraints, as well as the algorithm of the optimization are defined. In the analysis run step, the algorithm searches for the best combination of the input values, in order to reach the objective function. The last step refers to the analysis of the optimization results.
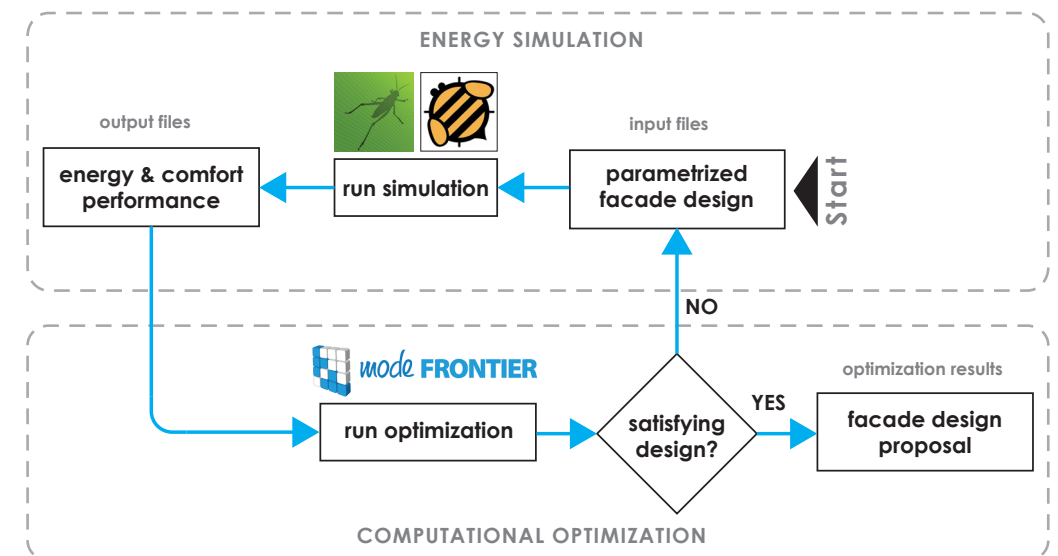

Figure 6.29: Developed workflow regarding the connection between GH and MF.

6.3.1. Workflow set-up

In ModeFrontier interface, the workflow tab offers information regarding how the optimization is organized, how the simulations are performed and which applications are used for the simulations. The graphical representation of the workflow presents the main parts of the optimization, namely, the inputs, the optimizer, the connection to GH, the outputs, the constraints and the objective (Figure 6.30).

For that study, the pilOPT optimizer is selected, because it allows a fast convergence with a relative low number of evaluations. It is a hybrid multi-strategy algorithm, offering the advantages of both local and global search algorithms. It takes advantage of the available design evaluation time, adjusting dynamically the ratio of virtual and real design evaluations, according to their performance. Therefore, the pilOPT optimizer has a high convergence rate, meaning it can converge to the optima quickly (modeFrontier, n.d.). The self-initializing mode is selected, with 200 evaluations and no Design of Experiments (DOE) is defined for that case, as it is not required for the pilOPT optimizer. Figures 6.31, 6.32 and 6.33 show the properties of the inputs, the objective and the constraints respectively, as defined in MF interface.
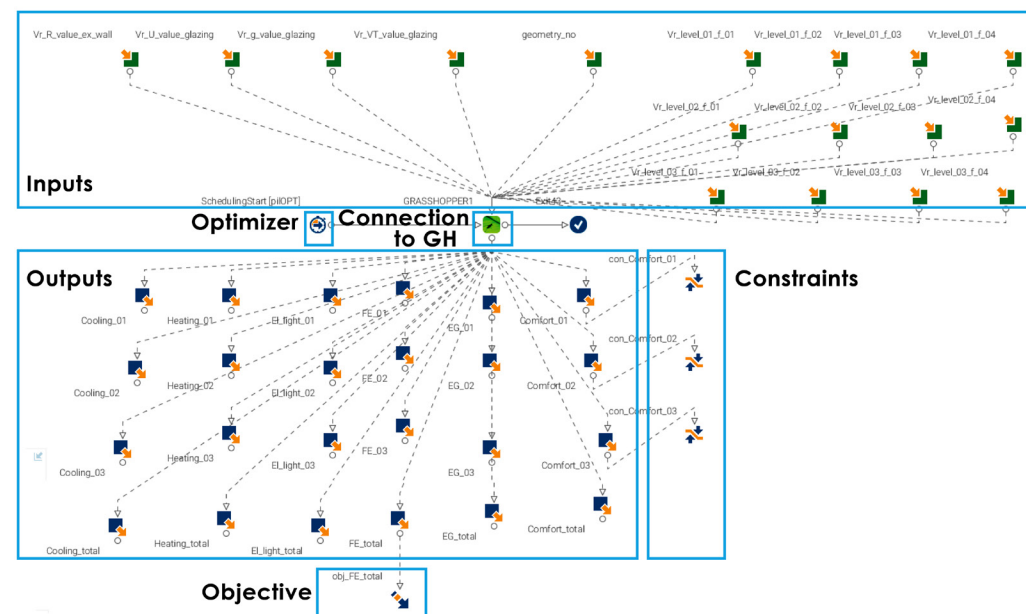

Figure 6.30: Workflow set-up for the optimization process in MF interface.

	Name	Type	Default Value	Lower Bound	Upper Bound			Base	Step
1	Vr_VT_value_glazing	Variable	-1.0	0.5	0.7	...	...	3	0.099...
2	Vr_level_03_f_04	Variable	0.0	0.0	5.0	...	...	6	1.0
3	Vr_R_value_ex_wall	Variable	-1.0	4.5	7.5	...	...	4	1.0
4	Vr_level_03_f_03	Variable	0.0	0.0	5.0	...	...	6	1.0
5	Vr_level_03_f_02	Variable	0.0	0.0	5.0	...	...	6	1.0
6	Vr_level_03_f_01	Variable	0.0	0.0	5.0	...	...	6	1.0
7	geometry_no	Variable	0.0	0.0	5.0	...	...	6	1.0
8	Vr_g_value_glazing	Variable	-1.0	0.3	0.5	...	...	3	0.1
9	Vr_level_01_f_04	Variable	0.0	0.0	5.0	...	...	6	1.0
10	Vr_level_01_f_03	Variable	0.0	0.0	5.0	...	...	6	1.0
11	Vr_level_01_f_02	Variable	0.0	0.0	5.0	...	...	6	1.0
12	Vr_level_01_f_01	Variable	0.0	0.0	5.0	...	...	6	1.0
13	Vr_level_02_f_04	Variable	0.0	0.0	5.0	...	...	6	1.0
14	Vr_level_02_f_03	Variable	0.0	0.0	5.0	...	...	6	1.0
15	Vr_level_02_f_02	Variable	0.0	0.0	5.0	...	...	6	1.0
16	Vr_level_02_f_01	Variable	0.0	0.0	5.0	...	...	6	1.0
17	Vr_U_value_glazing	Variable	-1.0	0.8	1.6	...	...	3	0.4

Figure 6.31: The input properties as determined for the optimization process in MF interface.

	Enabled	Name	User Expression	Type	Format
1	✔	obj_FE_total	FE_total	Minimize	0.0000E0

Figure 6.32: The objective properties as determined for the optimization process in MF interface.

	Enabled	Name	User Expression	Type	Limit	Tolerance	Format
1	✔	con_Comfort_01	Comfort_01	Greater Than	89.0	0.0	0
2	✔	con_Comfort_02	Comfort_02	Greater Than	89.0	0.0	0
3	✔	con_Comfort_03	Comfort_03	Greater Than	89.0	0.0	0

Figure 6.33: The constraints properties as determined for the optimization process in MF interface.

6.3.2. Design exploration

After obtaining the results of the optimization, the design exploration of the solution space is performed, in order to analyze and understand the results. From the 200 design evaluations, 173 are feasible and the rest are unfeasible, meaning that they do not meet the constraint set for the thermal comfort. Figure 6.34 (Final Energy vs Thermal Comfort) shows the convergence of the algorithm: the last designs, designs with a higher ID value, perform better regarding the energy performance, and they also reach high comfort levels. The designs are grouped in three categories. The first two categories (from left to right) include the unfeasible designs. The fact that there is a gap between the clusters is due to the combination of the variables; the discrete space does not allow the covering of some areas.

MF offers different post-processing, sophisticated data analytics tools that allow the designer explore the solution space. For example, the correlation matrix in Figure 6.35 presents the Pearson correlation between the variables and the outputs of the optimization. In that subchapter, at first, the effect of the tested facade parameters on the final energy and thermal comfort performance is analyzed. In order to explain the trends regarding the final energy, extra graphs showing the distribution of the designs regarding the different energy loads are also also presented. Later on, based on the design exploration, the research sub-questions are answered.

Figure 6.35: The correlation matrix shows the Pearson relation between the variables and the outputs of the optimization (exported by ModeFRONTIER2018R3).
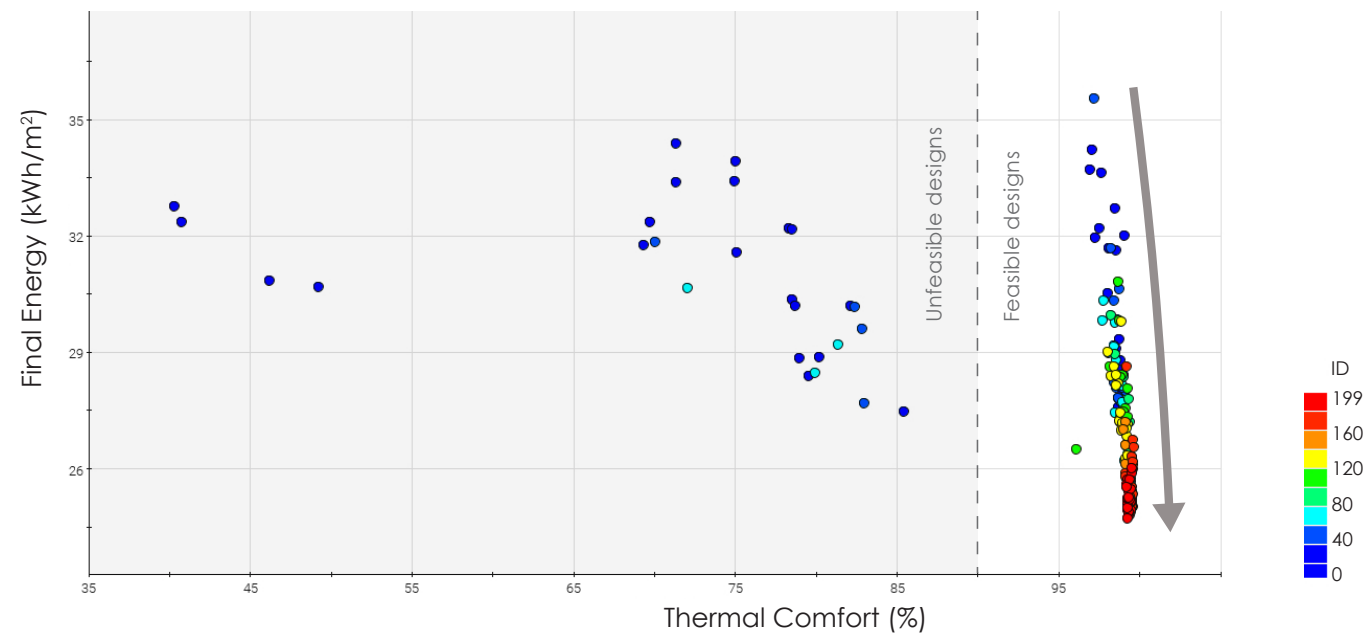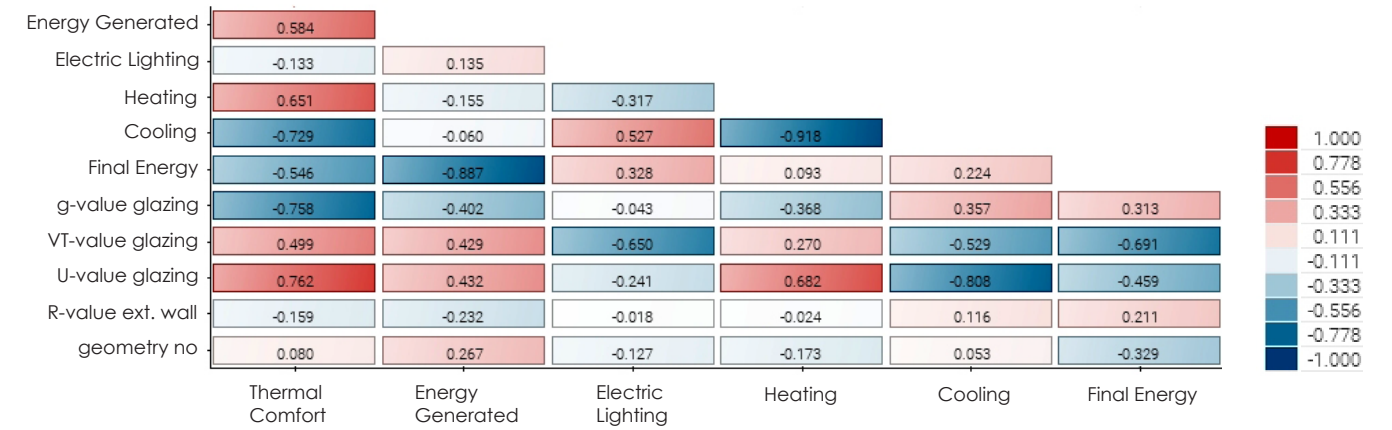

Figure 6.34: Ranking of designs based on their performance regarding the objective and the occupants' comfort (exported by ModeFRONTIER2018R3).
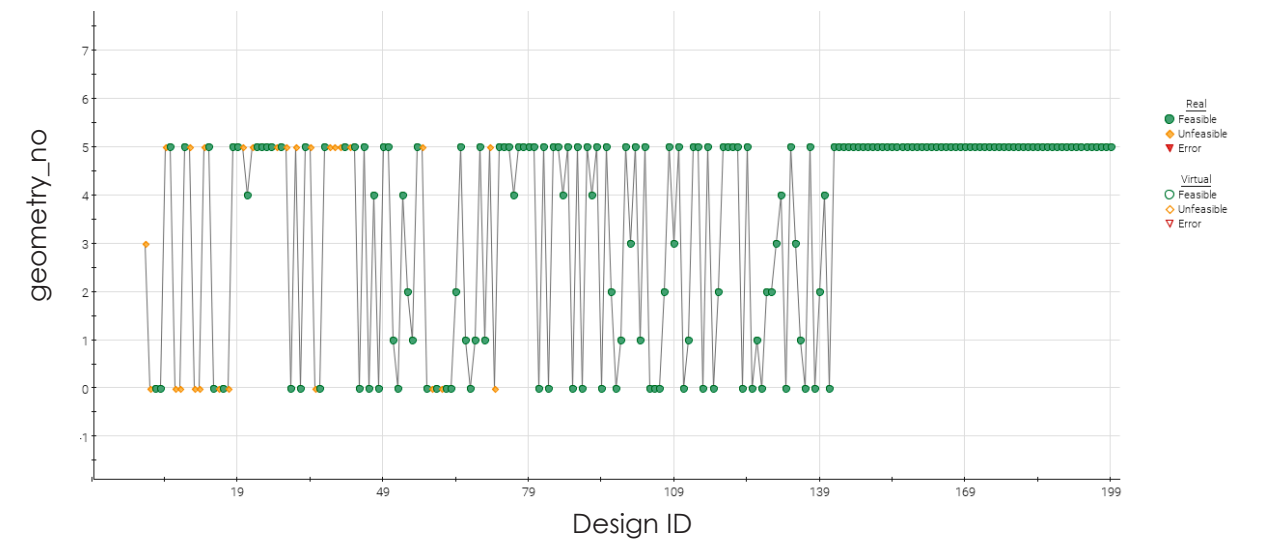

Figure 6.37: History chart showing the convergence of the algorithm to geometry no_05, based on the performance of designs regarding the objective (exported by ModeFRONTIER2018R3).

Distribution of designs regarding final energy and thermal comfort

Geometry type: shape and orientation

The bubble chart in Figure 6.36 shows how all designs, according to geometry types, are ranked based on their performance regarding the objective and the occupants' comfort. Geometries no_0 (rectangular shape, with the long side parallel to the north-south axis) and no_05 (square shape, rotated 45°) reach the minimum final energy levels, but the optimizer converges to geometry no_05 in the last 60 designs approximately, according to the history chart (Fig.6.37). The designs representing other geometry types are scattered in the solution space, and therefore, a trend based on the geometry type cannot be detected. In order to be able to rank the geometry types according to energy and comfort performance extra optimizations should run.

The geometry types no_0 and no_05 have less surface area towards north, which is beneficial for the energy performance of the building. Since all facades have BIPVs for the production of energy, it is logical that the north orientation is undesired, as less energy can be generated there (see Appendix 02, Fig.a.02.1). Furthermore, the square shape is more efficient than the tested rectangular shape, regarding the lighting load (Fig.6.51). In the rectangular shape the maximum depth of the office space is 9.90m, meaning that daylight is usually insufficient, and therefore the artificial lighting increases the final energy load. Last but not least, the square shape is more compact compared to the rectangular, and therefore, it has less external heat gains in summer and less heat loss in winter, resulting in low cooling and heating demand respectively (see Appendix 02, Fig.a.02.2).

Tested geometry types

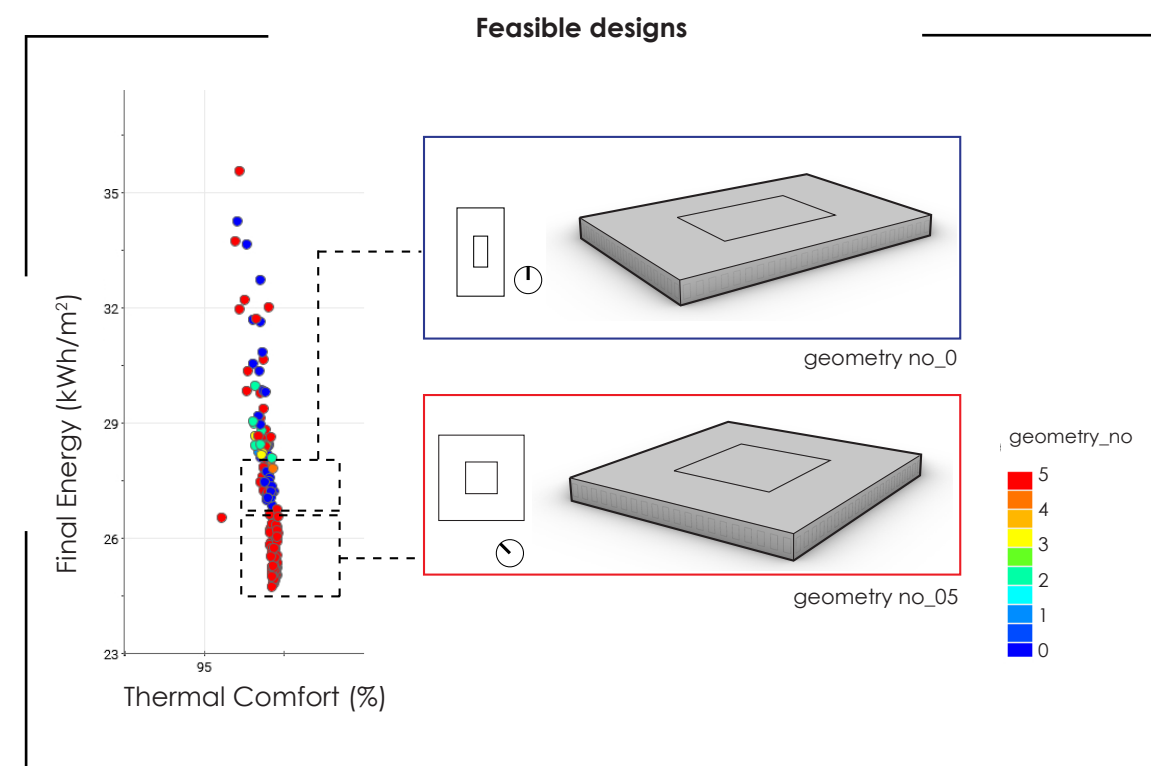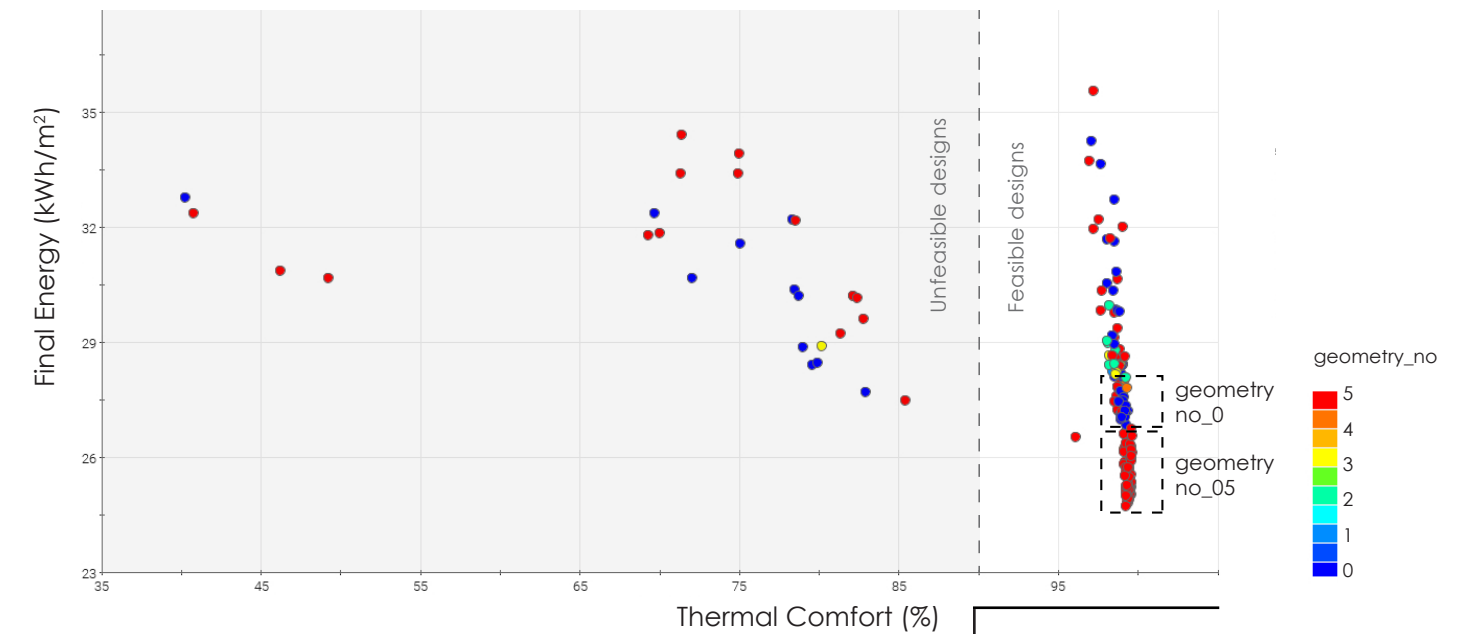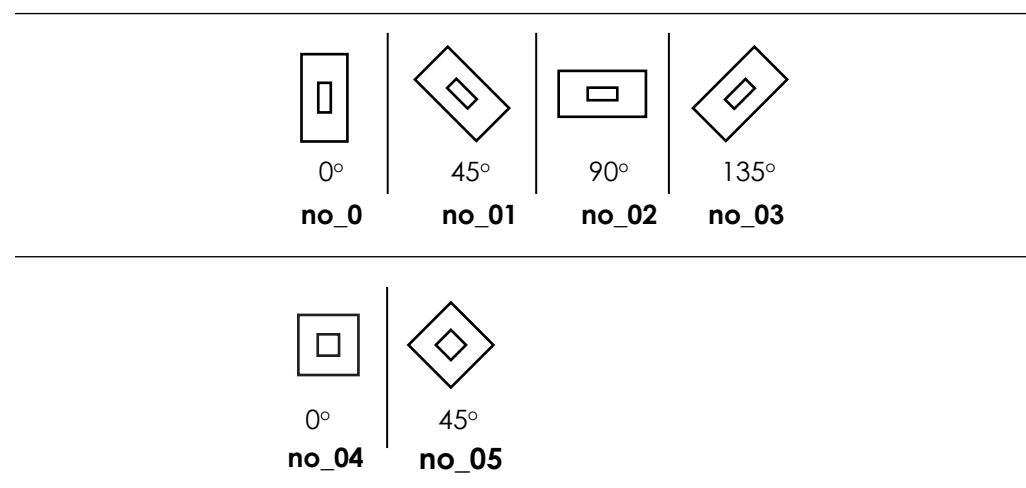| 0° | 45° | 90° | 135° |
| no_0 | no_01 | no_02 | no_03 |

| 0° | 45° |
| no_04 | no_05 |

Figure 6.36: Ranking of designs based on the geometry type, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).

g-value of glazing

According to the correlation matrix, the g-value of the glazing has a positive effect on the total final energy and a strong negative effect on the comfort. In order to meet the limit of the thermal comfort, a low g-value (0.3) is required (Fig. 6.38). The lower g-values of the glazing lead to lower solar heat gains during summer, and consequently to a lower cooling load (passive heating) (see Appendix 02, Fig.a.02.3). That is an important aspect for offices, as they have considerably high internal loads.
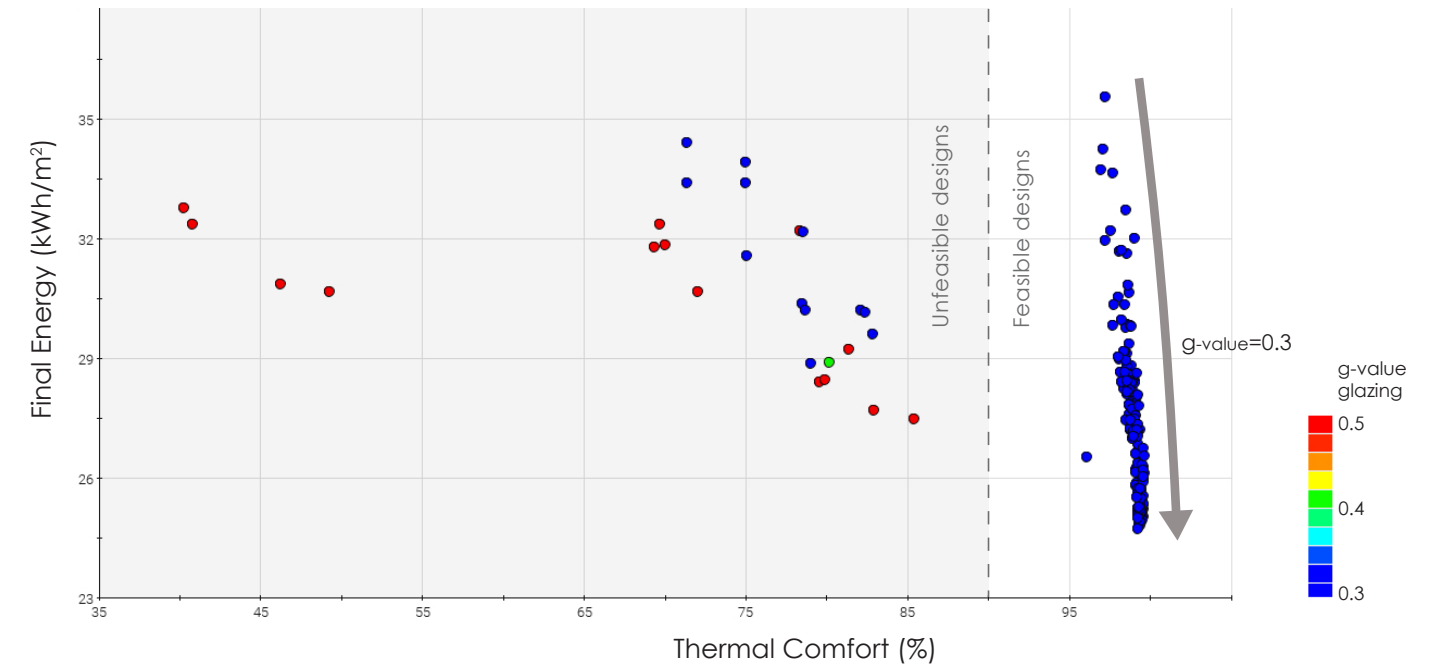

Figure 6.38: Ranking of designs based on the g-value of the glazing, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).

VT-value of glazing

The correlation matrix shows that the VT-value of the glazing has the highest negative effect on the total final energy (-0.691). According to the bubble chart, in Figure 6.39 (final energy vs thermal comfort), higher values of VT-value lead to lower final energy values. From that graph, it can also be observed that the VT-value does not affect the comfort: both low and high VT-values achieve high levels of comfort. Additionally, that parameter has the greatest negative correlation with the lighting load (0.650). Higher VT-values allow more daylight into the office space, therefore minimizing the lighting load, which is high for that kind of buildings (Fig.6.52). Also, since high VT-values minimize the lighting load, the internal loads in the office space are minimized as well, resulting in low cooling loads in summer (see Appendix 02, Fig.a.02.4).
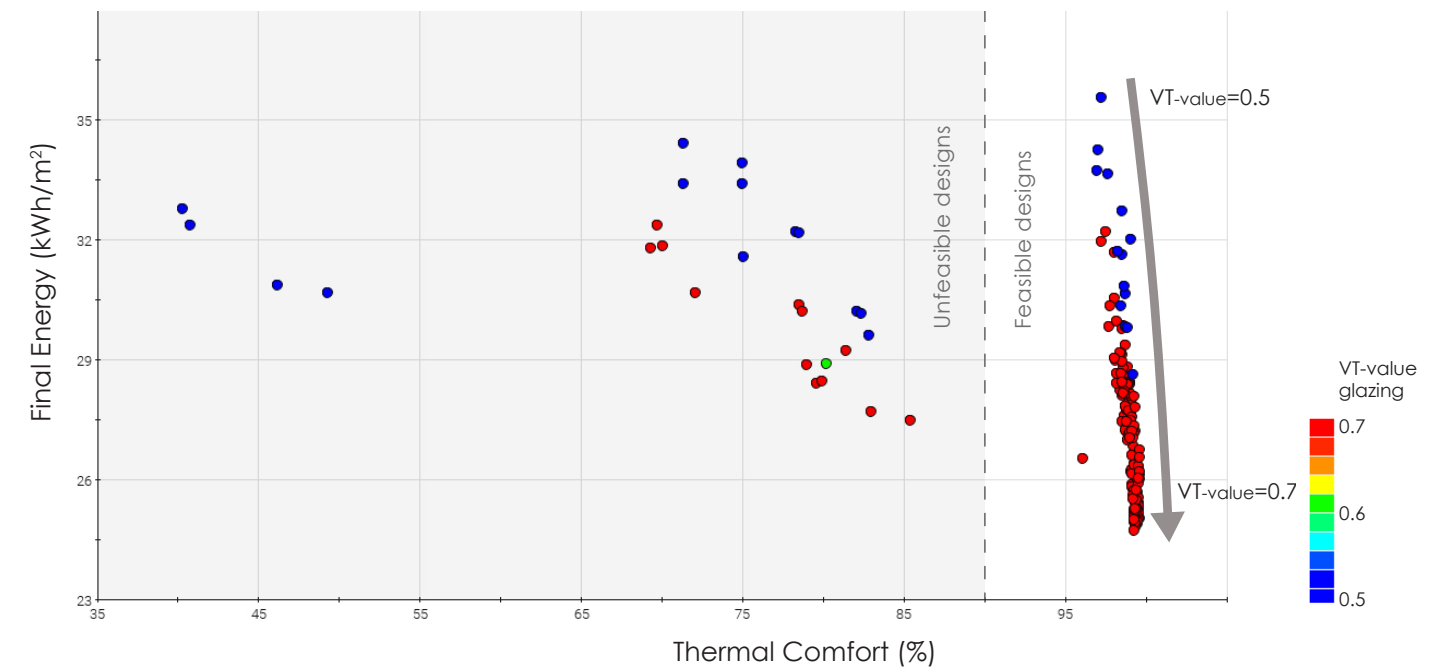

Figure 6.39: Ranking of designs based on the VT-value of the glazing, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).

U-value of glazing

A high U-value for the glazing (1.6 W/m²-K) is required, regarding both the final energy and the comfort requirement (Fig. 6.40). That parameter has a high positive relation (0.682) with the heating load and a stronger negative relation with the cooling load (-0.808). That means that a low U-value would be better for winter, and a high U-value would be better for summer. Due to high internal loads in office spaces, higher U-values are preferred, as they help to avoid overheating during the summer months (see Appendix 02, Fig.a.02.5).

It should be noted that the building has a mixed-mode ventilation system, meaning that when the building runs on natural ventilation, the latter dominates the U-value of the glazing. The natural ventilation is activated when the outdoor temperature is between 21 and 25°C. That means that for the period of time that the natural ventilation is not activated, because the temperature criteria are not met, there is still a lot of heat in the building that needs to be extracted. Therefore, it can be concluded that the temperature limits that control the natural ventilation should be redefined. What is more, regarding the effect of the U-value to the final energy, one should also take into account the w/w ratios of the facades. Smaller w/w ratios allow a higher U-value.
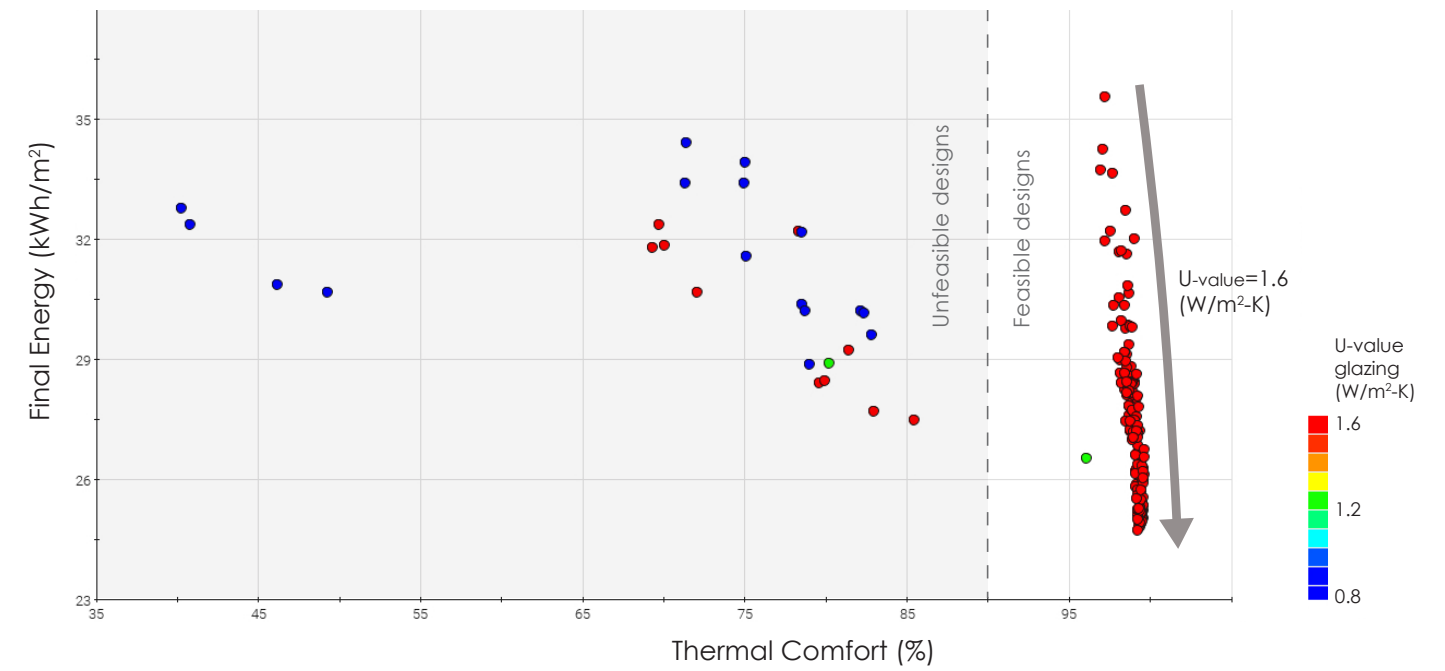

Figure 6.40: Ranking of designs based on the U-value of the glazing, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).

R-value of exterior wall

The trend between the R-value and the objective is not that clear. However, it is noticed that a value of 5.5 m²-K/W is preferred regarding the objective (Fig. 6.41). That value also meets the comfort requirement. Higher R-values are expected to increase the transmission losses during winter, thus maximizing the heating load. Also, lower R-values are expected to increase the cooling load in summer months, while natural ventilation is not activated, as the accumulated heat could not be extracted from the office space.
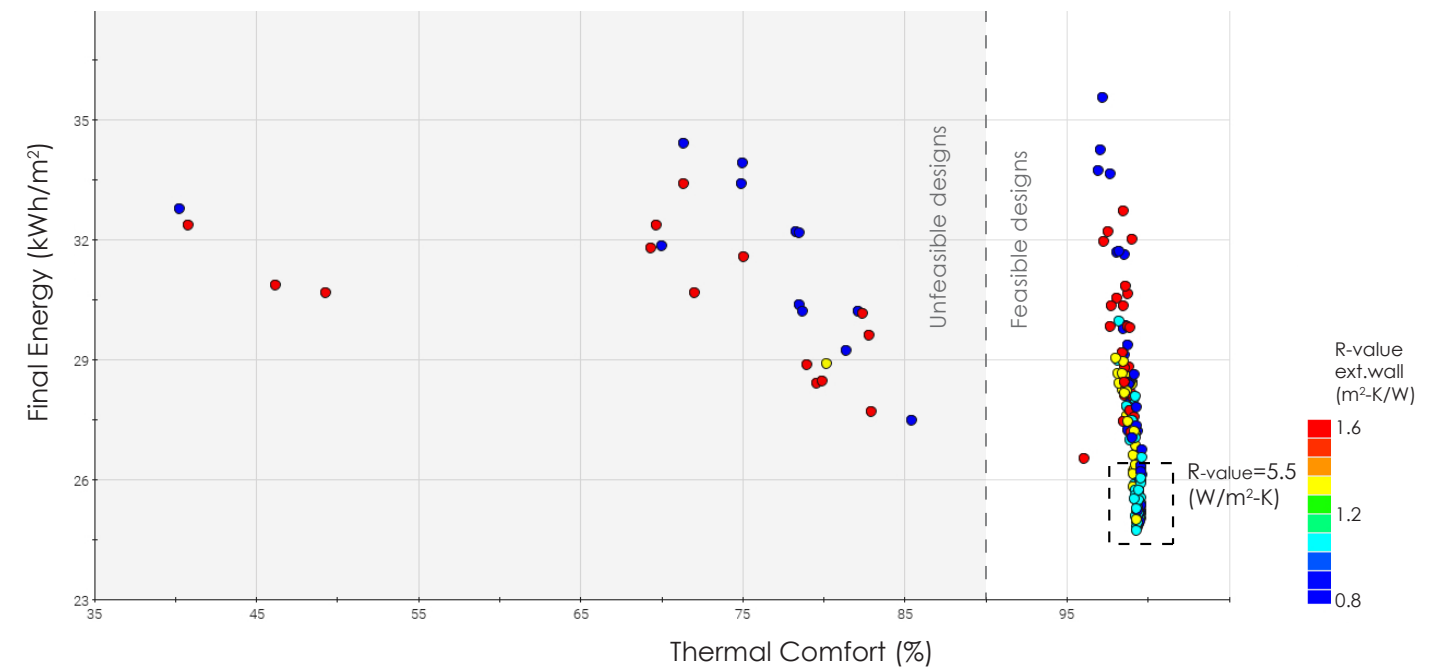

Figure 6.41: Ranking of designs based on the R-value of the exterior wall, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).

w/w ratio

Specifically for geometry_05, which includes the best performing designs, the effect of the w/w ratio per orientation on the final energy and the thermal comfort is presented on Figure 6.42. The w/w ratio in all orientations has a great relation to the energy generated. Lower w/w ratios result in more surface area for BIPVs, which produce energy, and therefore minimize the final energy (Fig. 6.47-6.50). That is why low values of w/w ratio are mostly preferred in all facades (Fig. 6.43-6.46).

The best performing designs for south-oriented facades feature a 30% or 40% w/w ratio, as they are explosed to a high amount of solar radiation annually. The north-oriented façades have quite higher suggested w/w ratios (up to 50%). That could be explained as these façades collect less radiation and daylight in that climate, and therefore higher w/w ratios in north oriented facades lead to higher solar gains and daylight levels.
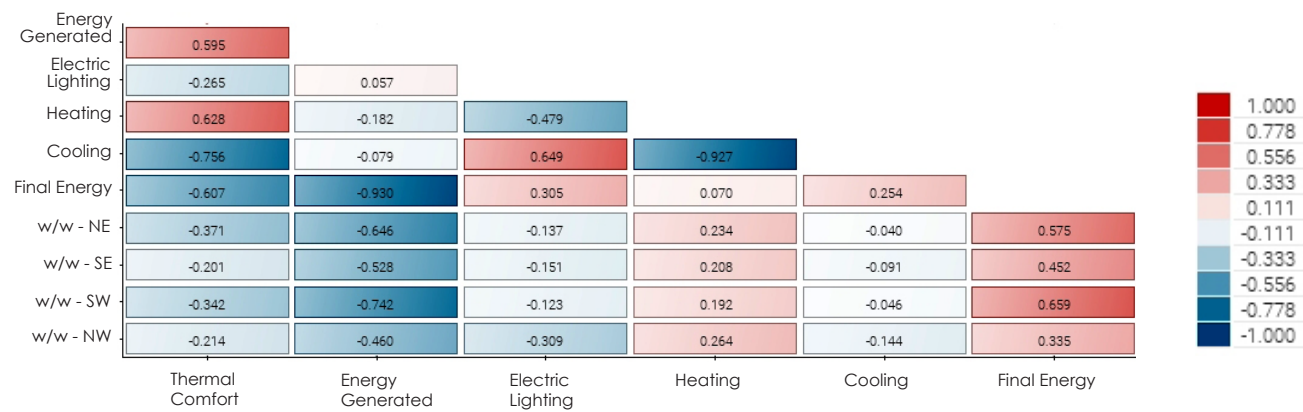
Pearson correlation chart

Figure 6.42: The correlation matrix shows the Pearson correlation between the w/w ratio, regarding orientation, and the outputs of the optimization for geometry_05 (exported by ModeFRONTIER2018R3).

South oriented facades

Figure 6.43: Ranking of designs based on the w/w ratio of the south-west facade, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

Figure 6.44: Ranking of designs based on the w/w ratio of the south-east facade, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

North oriented facades
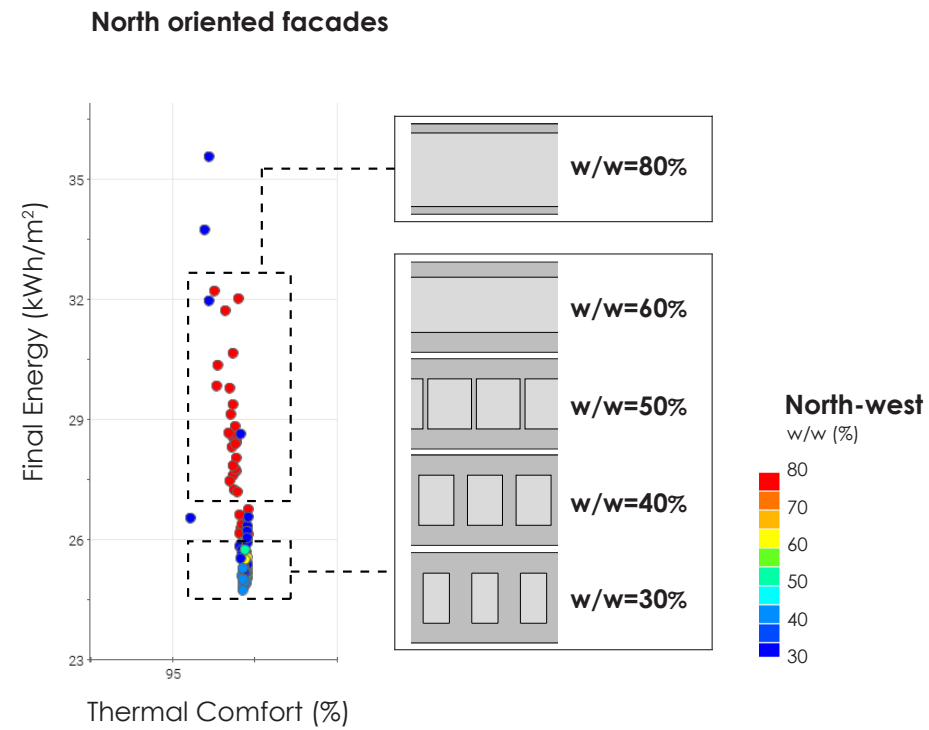
Figure 6.45: Ranking of designs based on the w/w ratio of the north-west facade, regarding the final energy and the occupants' comfort (exported by ModeFRONTIER2018R3).
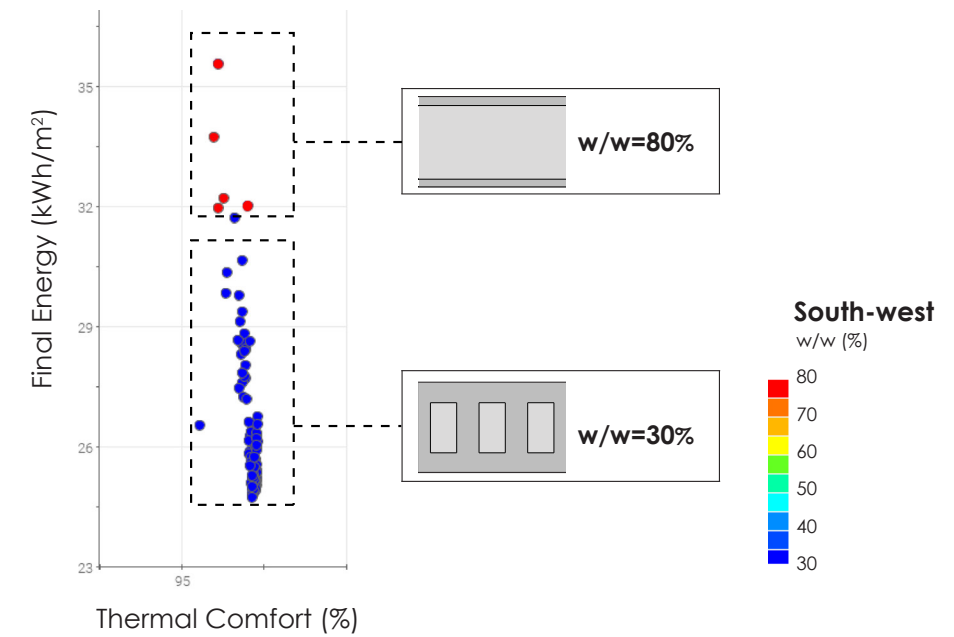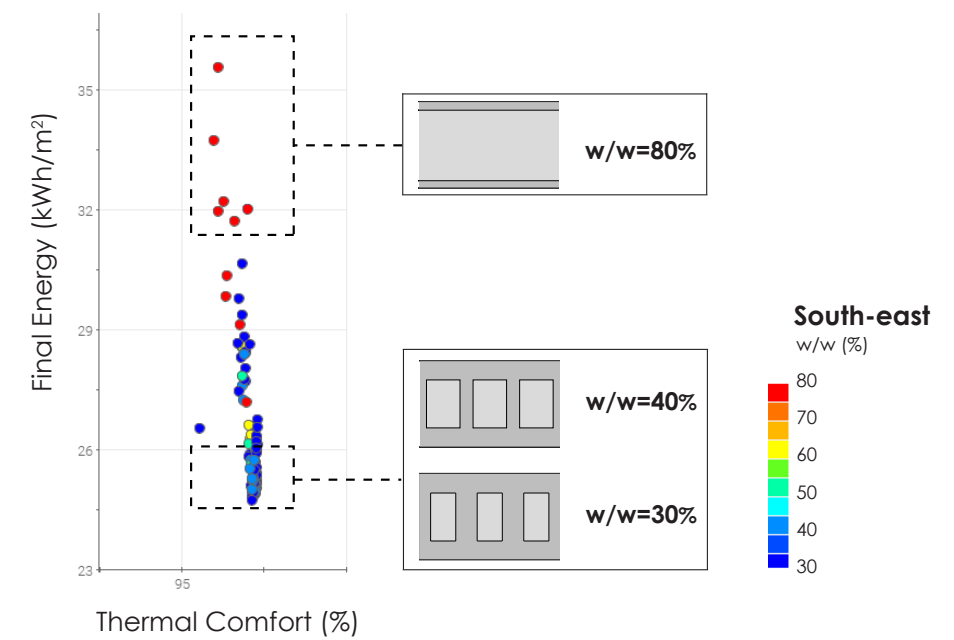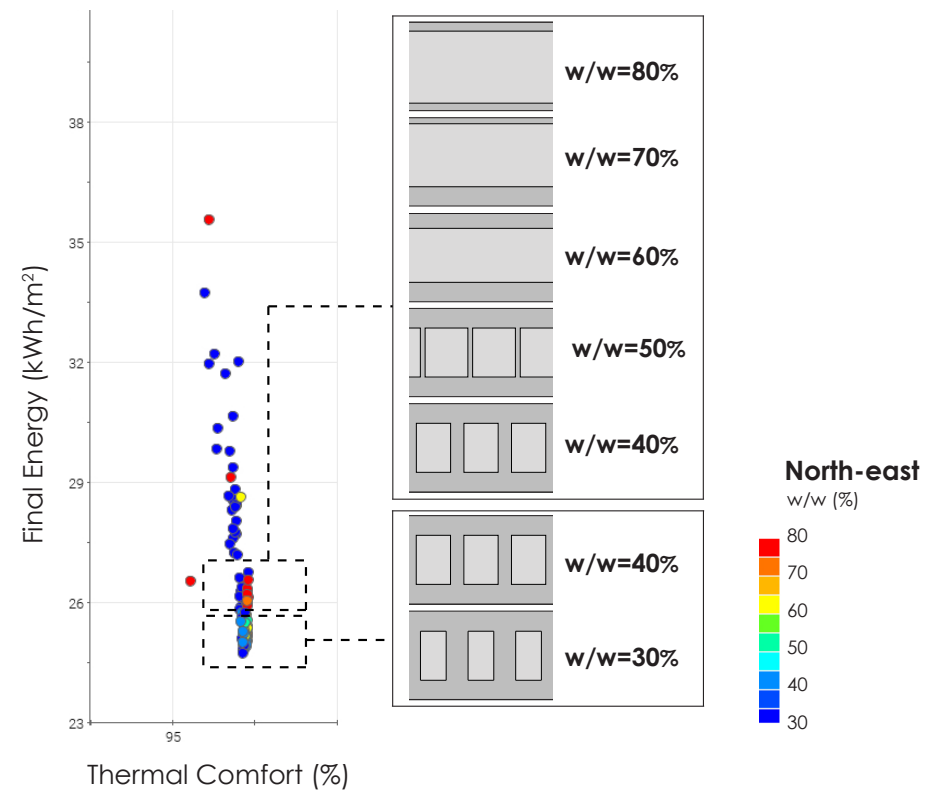

Figure 6.46: Ranking of designs based on the w/w ratio of the north-east facade, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

Distribution of designs regarding final energy and energy generated

South-oriented facades

Figure 6.47: Ranking of designs taking into account south-west orientation, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).
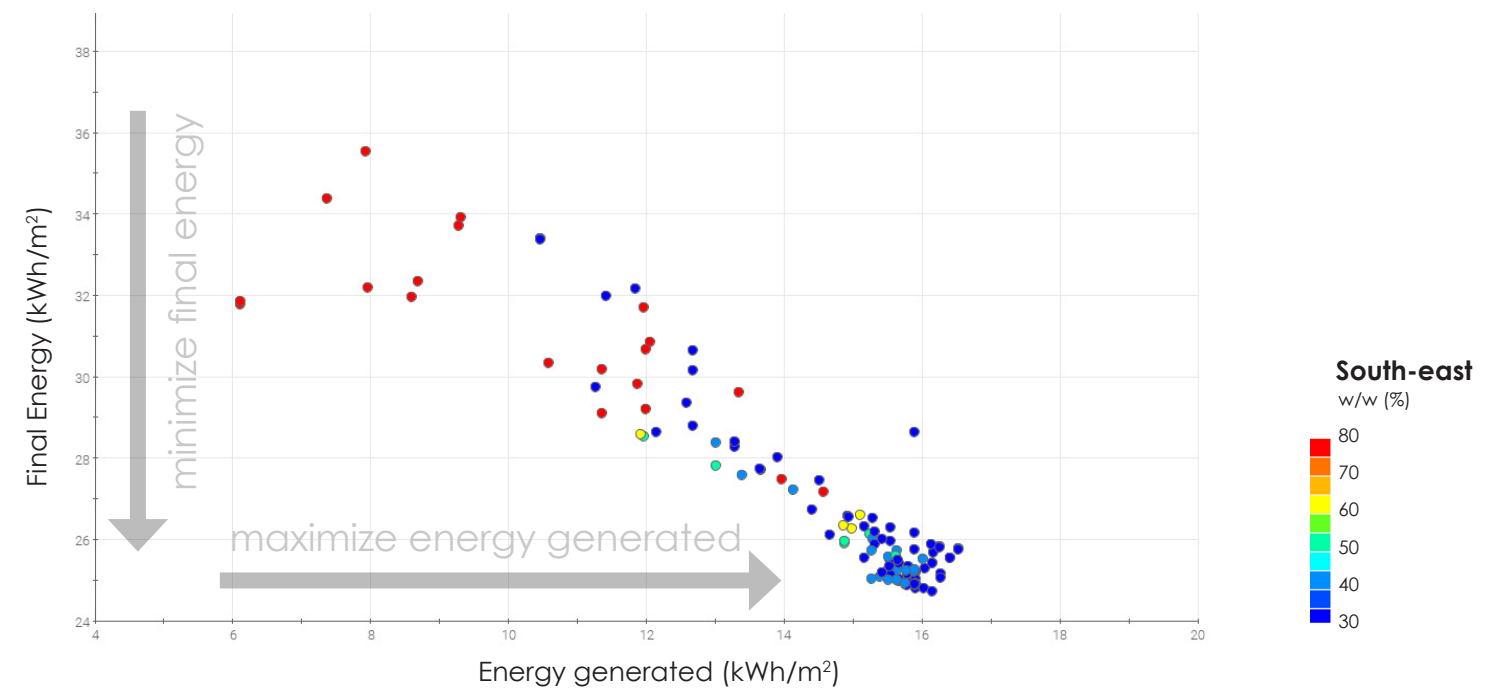
Figure 6.48: Ranking of designs taking into account south-east orientation, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

Distribution of designs regarding final energy and lighting load

North-oriented facades

Figure 6.49: Ranking of designs taking into account north-west orientation, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

Geometry type

Figure 6.51: Ranking of designs based on the geometry type, regarding the final energy and the lighting load (exported by ModeFRONTIER2018R3).
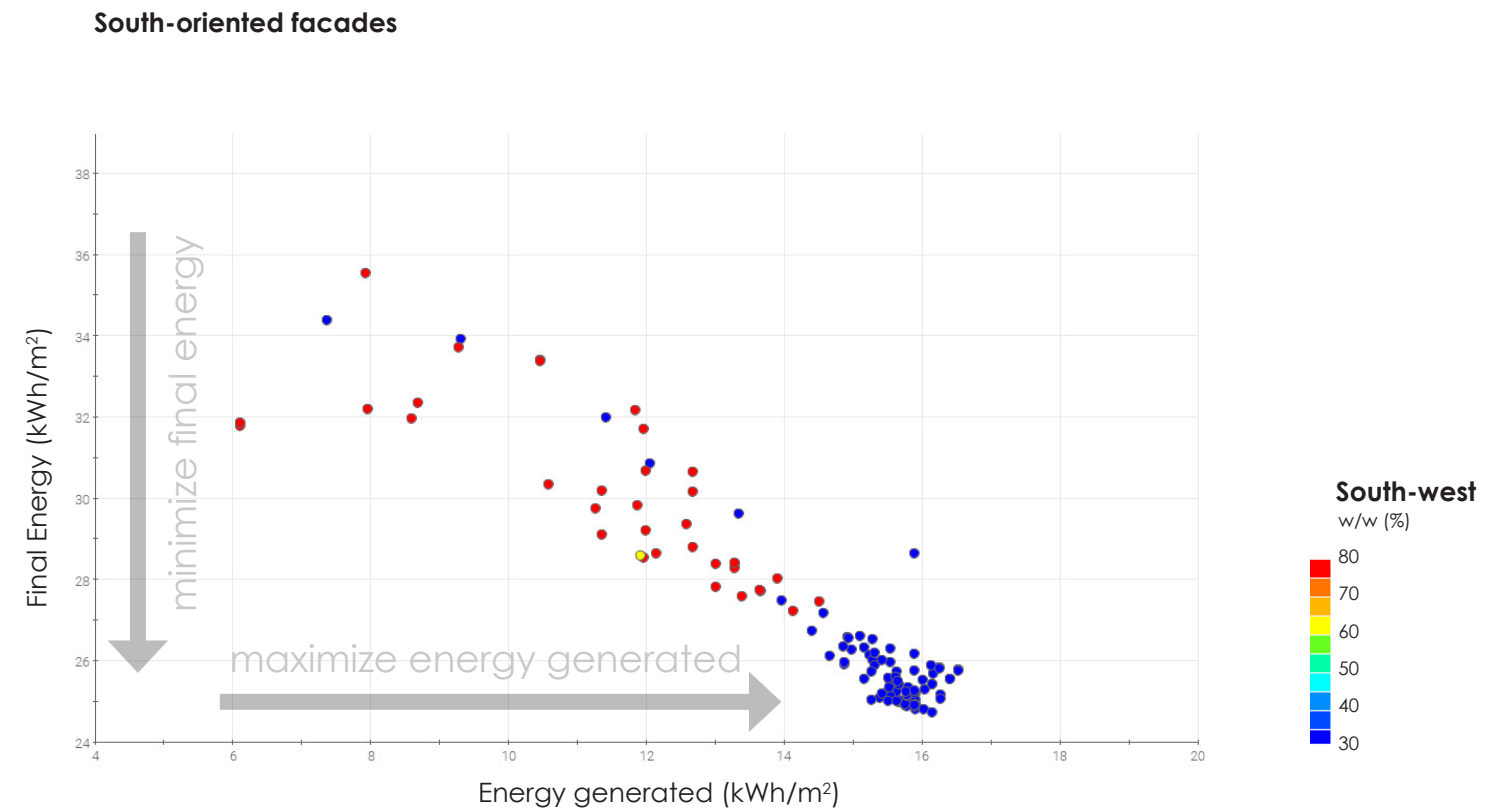

Figure 6.50: Ranking of designs taking into account north-east orientation, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).
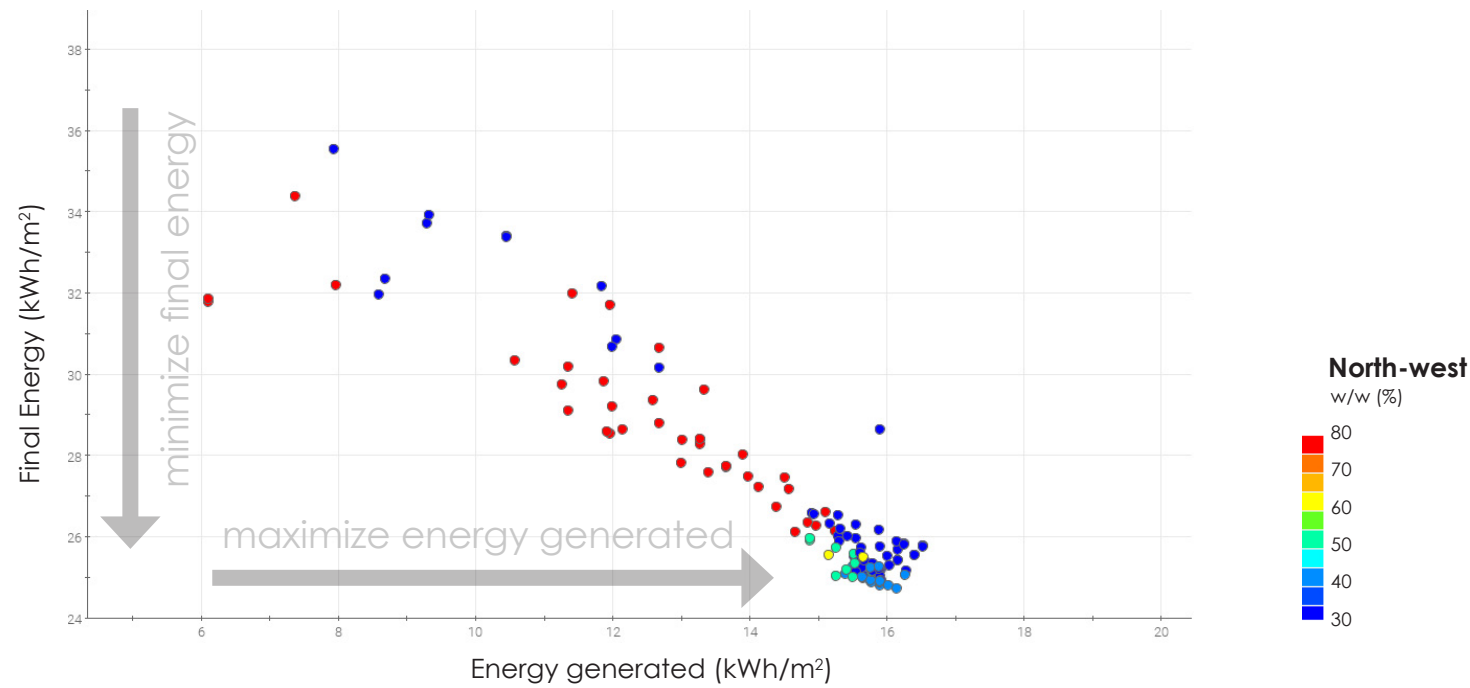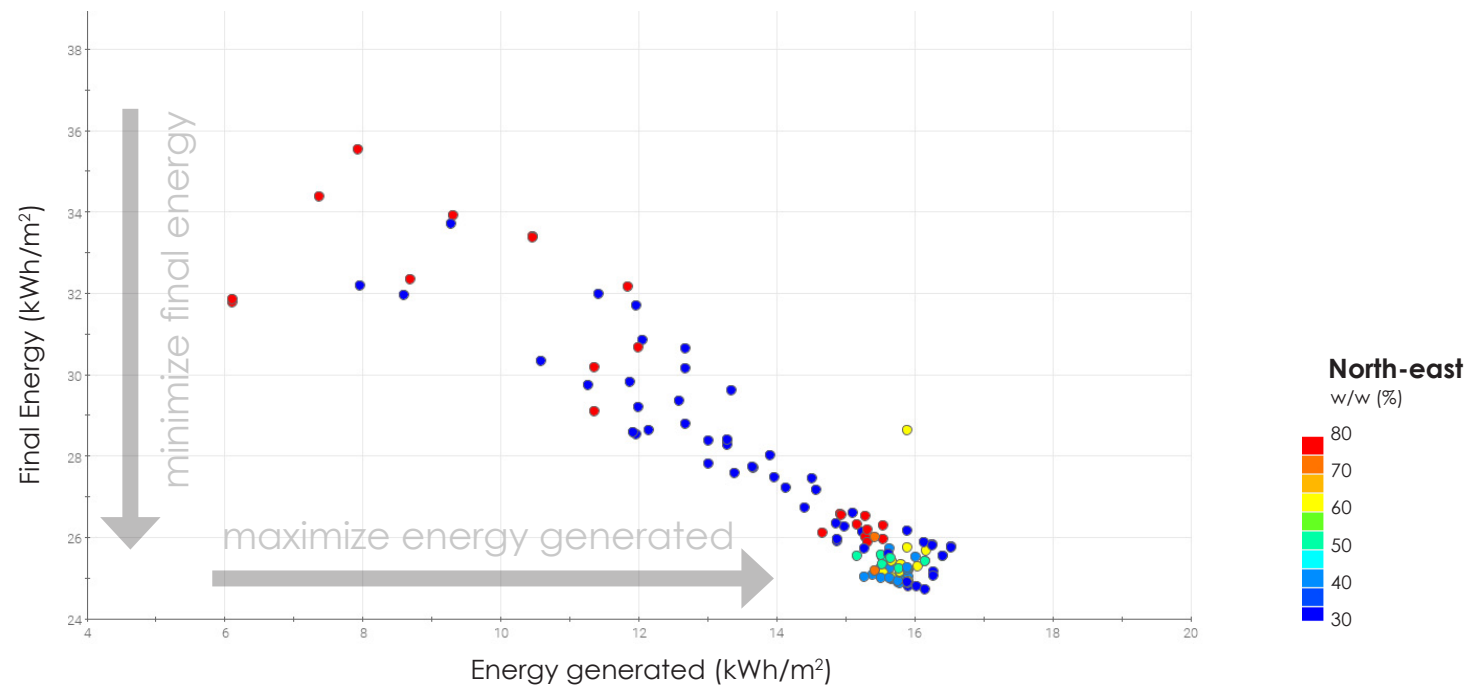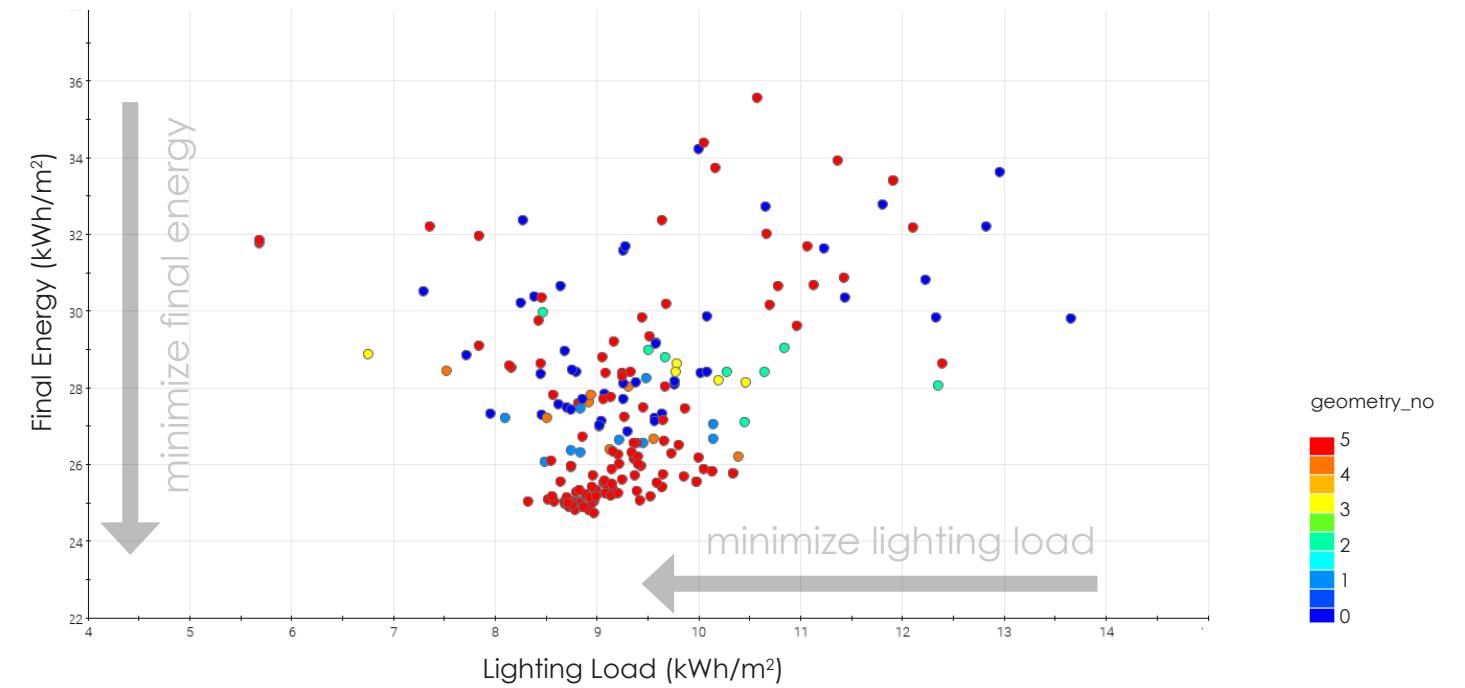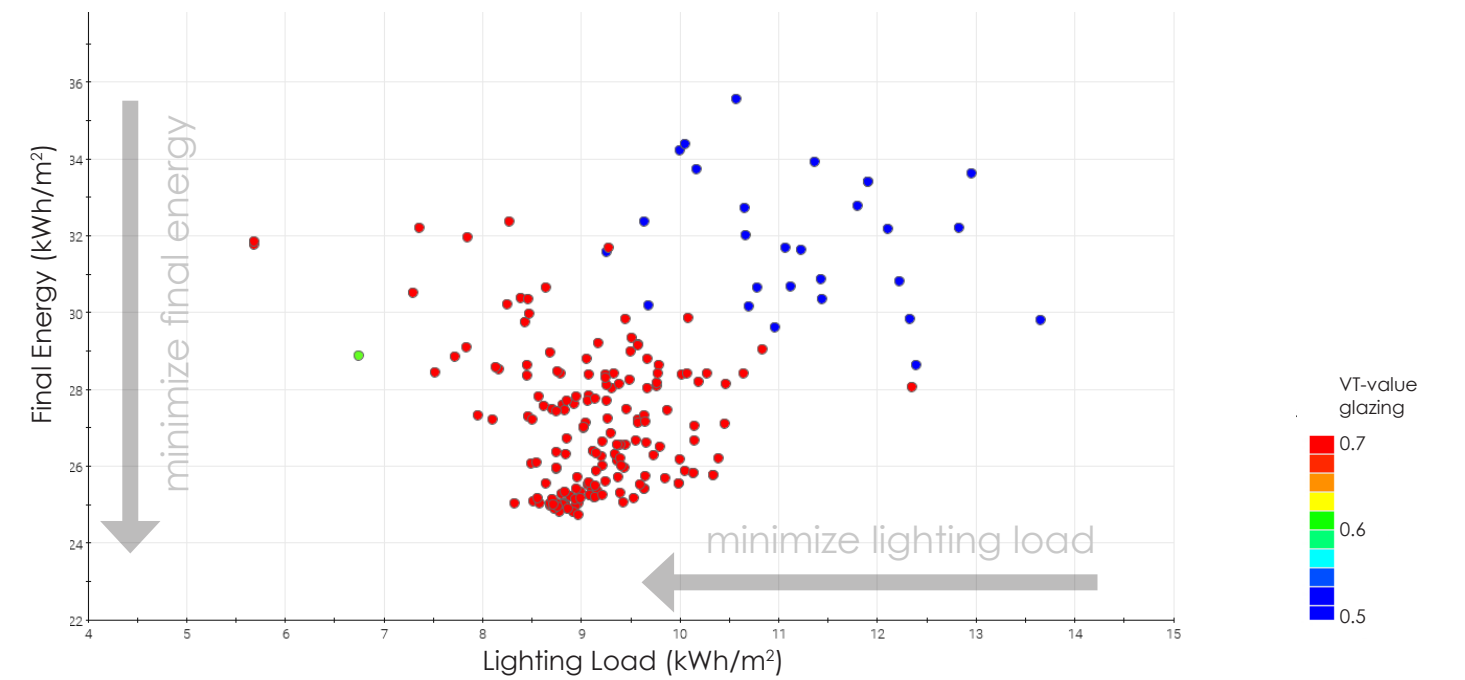
VT-value of glazing

Figure 6.52: Ranking of designs based on the VT-value of the glazing, regarding the final energy and the lighting load (exported by ModeFRONTIER2018R3).

Filtering out designs with the parallel coordinate chart

With the parallel coordinate chart, the designer can filter out designs from the solution space, setting limits to either the tested variables, or the outputs of the optimization. In that way, only the designs that fulfil those requirements are selected. The parallel coordinate chart is useful for the decision making, as one can vizualise the range of the designs that meet the spesific criteria.

Figure 6.53 shows the range of all tested facade properties in order to reach relatively low final energy levels (24.7-26.0 kWh/m²), and also accepted thermal comfort levels (90-100%). It is obvious that for some parameters only one value is suggested, e.g. a solar energy transmittance (g-value glazing) of 0.3, while for others, a wider range of values is possible. For example, the w/w ratio for the north-east facade, for geometry no_5, has a wide range: 30-80%, meaning that that parameter does not have a big effect on the set criteria.
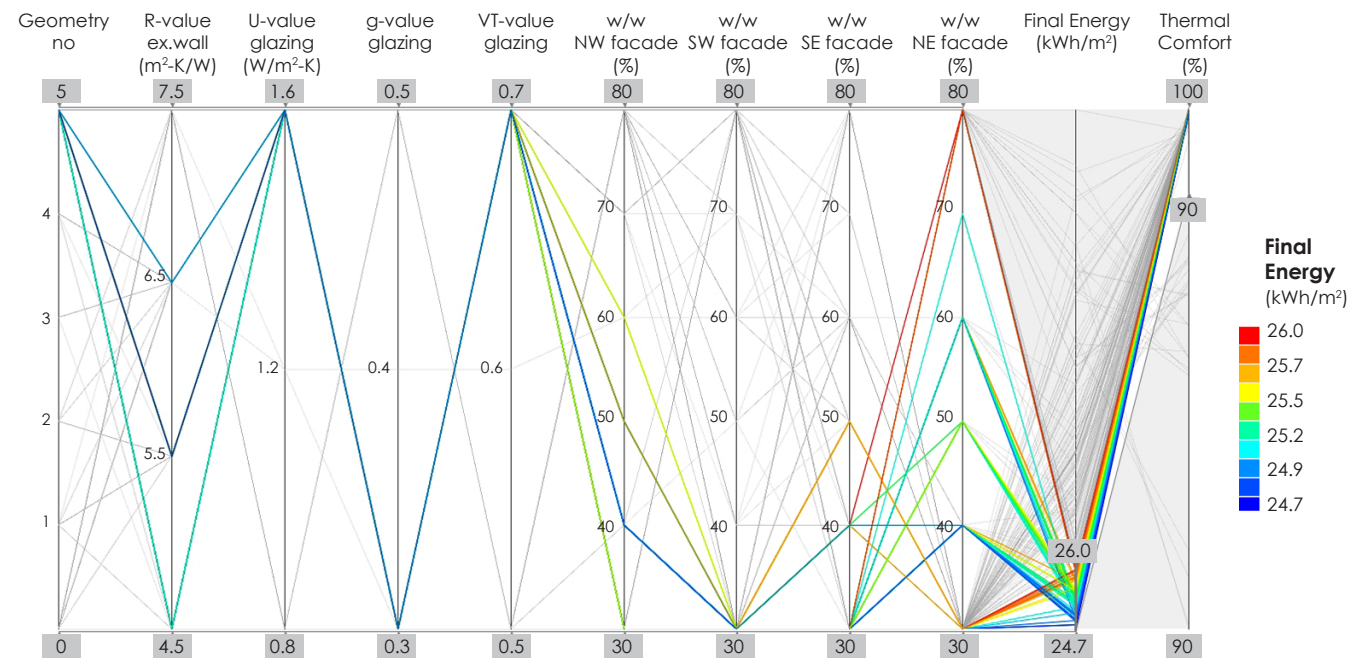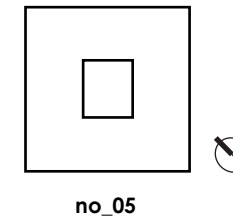
The most effective combination of façade design parameters that can lead to a nearly Zero - Energy high-rise office building in the temperate climate

no_05

design_no	1	2	3	4	5
geometry_no	5	5	5	5	5
R-value ext. wal (m2-K/W)	5.5	5.5	5.5	5.5	6.5
U-value glazing (W/m2-K)	1.6	1.6	1.6	1.6	1.6
g-value glazing	0.3	0.3	0.3	0.3	0.3
VT-value glazing	0.7	0.7	0.7	0.7	0.7
w/w - level 01 - NW (%)	40	40	40	40	40
w/w - level 01 - SW (%)	30	30	30	30	30
w/w - level 01 - SE (%)	30	30	30	30	40
w/w - level 01 - NE (%)	30	30	40	40	50
w/w - level 02 - NW(%)	40	40	40	40	40
w/w - level 02 - SW (%)	30	30	30	30	30
w/w - level 02 - SE (%)	30	30	30	30	30
w/w - level 02 - NE (%)	30	50	40	50	30
w/w - level 03 - NW (%)	40	40	40	40	40
w/w - level 03 - SW (%)	30	30	30	30	30
w/w - level 03 - SE (%)	30	30	30	30	30
w/w - level 03 - NE (%)	30	30	30	30	30
Final Energy (total) (kWh/m2)	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (total) (%)	99	99	99	99	99

Table 6.4: Façade design parameters of the five best performing designs among all geometry types.

Figure 6.53: Filtering out designs, in order to reach low final energy levels and acccepted thermal comfort levels (exported by ModeFRONTIER2018R3).

In general, among all geometry types, geometry no_05 performs the best. The five best performing designs (with the lowest value of total final energy) are selected, and the façade design parameters of these designs are presented, in order to identify trends (Table 6.4). It is noticed that designs with lower values of w/w ratio for all orientations are selected, since that leads to lower heat losses during winter and lower solar gains at summer. In addition, lower w/w ratios result in higher surface area for BIPVs, which generate energy with 16% efficiency, resulting in lower final energy. North-east and north-west facades have a slightly higher w/w ratio (40-50%) compared to the other orientations, as explained before. The best performing designs have the highest possible VT-value for the glazing (0.7), in order to decrease the lighting load. What is more, all selected designs have the minimum possible g-value of the glazing (0.3).

Regarding the relation of the g and VT value, the LSG value of the glazing type that the optimization results suggest is 2.33, which is considered high compared to the average LSG values of current glazing products in the market. However, the suggested value is feasible, as table 3.4 shows. For example, a clear double-glazed pane with a low-solar-gain low-E coating has a low g-value (0.27) and a high VT value (0.64), resulting in a LSG value of 2.37 (Efficient Windows Collaborative, n.d.).

The energy breakdown and the comfort performance for the best performing façade designs of a nearly Zero - Energy high-rise office building in the temperate climate

	design_no	1	2	3	4	5
Cooling Load (kWh/m2)	level 01	9.1	9.1	9.1	9.1	9.0
	level 02	9.1	9.0	9.0	9.0	9.1
	level 03	9.1	9.1	9.1	9.1	9.1
	total	9.1	9.1	9.1	9.0	9.1
Heating Load (kWh/m2)	level 01	22.7	22.7	22.8	22.8	22.9
	level 02	22.8	23.0	22.9	23.0	22.8
	level 03	22.8	22.8	22.8	22.8	22.8
	total	22.8	22.9	22.9	22.9	22.8
Lighting Load (kWh/m2)	level 01	9.0	9.0	8.8	8.8	8.0
	level 02	9.0	8.4	8.8	8.4	9.0
	level 03	9.0	9.0	9.0	9.0	9.0
	total	9.0	8.8	8.9	8.7	8.6
Energy Generated (kWh/m2)	level 01	16.1	16.1	15.8	15.8	14.6
	level 02	16.1	15.4	15.8	15.4	16.1
	level 03	16.1	16.1	16.1	16.1	16.1
	total	16.1	15.9	15.9	15.8	15.6
Final Energy (kWh/m2)	level 01	24.7	24.7	24.9	24.9	25.3
	level 02	24.7	25.0	25.0	25.0	24.7
	level 03	24.7	24.7	24.7	24.7	24.7
	total	24.7	24.8	24.9	24.9	24.9
Thermal Comfort (%)	level 01	99	99	99	99	99
	level 02	99	100	99	100	99
	level 3	99	99	99	99	99
	total	99	99	99	99	99

Table 6.5: Breakdown of final energy and comfort for the five best performing designs among all geometry types.

From Table 6.5, it can be observed that the heating demand has the highest value among other types of energy load. The energy produced by the BIPVs is much higher than the cooling load or the lighting load; it is almost the double of the lighting load. It should be noted that the energy generated is only affected by the w/w ratio, since the nearby buildings are not taken into account in the simulations, resulting in these significantly high values of energy generated. What is more, comfort levels are extremely high for all the best performing designs, more than 99%. It should also be noted that there is not a considerable difference between the performance of the three floors, as the building has a high degree of air-tightness.

6.3.3. Evaluation according to BENG

The best performing buildings are evaluated according to BENG requirements. For that research, the calculation of the performance regarding energy and comfort is performed with dynamic calculations in GH (Honeybee), and it does not follow the NTA 8800 standards. As described in chapter 2.2, for BENG 1, the heating and cooling energy demand is taken into account, without considering heat recovery. Since heat recovery is used for the simulations in that study, only BENG 2 and BENG 3 requirements are considered for the evaluation.

Regarding BENG 2, in order to calculate the delivered energy, a COP of 5 and a COP 5.5 are considered for heating and cooling accordingly. For BENG 2, the lighting load is also added to the energy load, since it is a commercial building. For that research, the energy for heating the water is considered to be zero, since it is an office building. What is more, the energy for fans and pumps is added, while the produced energy by the BIPV panels is subtracted by the calculated energy, according to BENG 2 requirement. In order to determine the primary energy, the calculated energy is multiplied by the primary energy factor. According to NTA 8800 standards, the primary energy factor is a conversion factor per energy carrier, with which the calculated amount of energy "on the meter" is converted to primary energy. For the case that the energy carrier is electricity, the primary energy factor is 1.45.

The table 6.6 and Figure 6.54 present the primary energy for the five best performing designs. For all designs, the energy load is almost equal to the energy generated, resulting in nZEBs. All designs comply with the BENG 2 requirement, 40 kWh/m^2 for office buildings, and perform exceedingly better than that limit.

Design	Heating Load (kWh/m2)	Cooling Load (kWh/m2)	Lighting Load (kWh/m2)	Fan & Pumps Electric (kWh/m2)	Energy Generated (kWh/m2)	Delivered Energy (kWh/m2)	Primary Energy (kWh/m2)
1	22.8	9.1	9.0	5.5	16.1	4.5	6.6
2	22.9	9.1	8.8	5.5	15.9	6.2	9.0
3	22.9	9.1	8.9	5.7	15.9	6.2	9.0
4	22.9	9.1	8.7	5.7	15.8	6.2	9.0
5	22.8	9.1	8.6	5.7	15.6	6.2	9.0

Table 6.6: Calculation of the primary energy (kWh/m2) for the five best performing designs.

Design	Energy Generated (kWh/m2)	Primary Energy (kWh/m2)	Energy Generated / (Primary Energy+Energy Generated) *100 (%)
1	16.1	6.6	71
2	15.9	9.0	64
3	15.9	9.0	64
4	15.8	9.0	64
5	15.6	9.0	63

Table 6.7: Calculation of the share of renewable energy (%) for the five best performing designs.
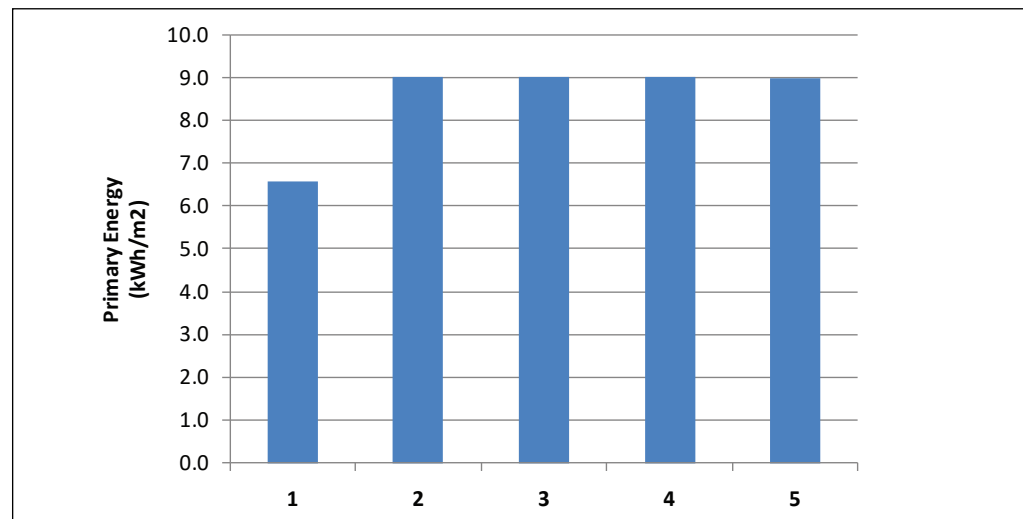
Figure 6.54: Ranking of the five best performing designs according to the primary energy (kWh/m2).
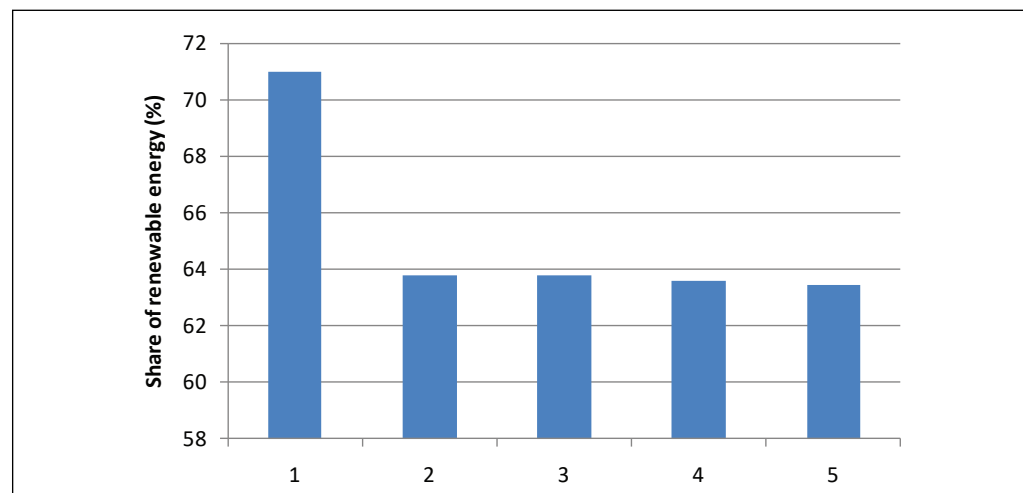

Figure 6.55: Ranking of the five best performing designs according to the share of renewable energy.

Regarding the BENG 3 indicator, the renewable energy is divided by the sum of the primary energy use and the renewable energy (Rijksdienst voor Ondernemend Nederland, n.d.). The minimum value for the share of renewable energy is 30%, according to BENG 3 requirement. All five designs exceed the limit significantly (Table 6.7 and Fig. 6.55).

6.3.4. Improvement of energy performance according to benchmark

The existing building, the Rotterdam Science tower, is used as benchmark for quantifying the improvement of the energy performance through the suggested workflow: the best performing design, obtained from the optimization, is compared with the existing building. The information for the technical façade properties of the tower was derived from the engineering report, from the archive of the municipality of Rotterdam.

The detailing of the façade is presented in Figure 6.56 (see Appendix 03, Figures a.03.1 - a.03.4). From the exterior to interior, the existing facade consists of light-coloured travertine plates (45mm), air cavity (45mm), expanded polystyrene (EPS) (20mm) and beton (primary structure) (560mm). Regarding the glazing, the windows have solar bronze glass (10mm), which is dark and reflective, and anodized aluminum frames. The building runs only on mechanical ventilation: the air exchange rate is 85 m³/h/person in the perimeter zone, and 120 m³/h/person in the core. Since the study focuses on the façade design optimization, only the façade characteristics are taken into account for that comparison. Other parameters, such as the construction of the floor/ceiling, the internal loads and the HVAC system are kept constant as the previously presented simulations, in order to highlight the effect of façade design choices to the energy performance.
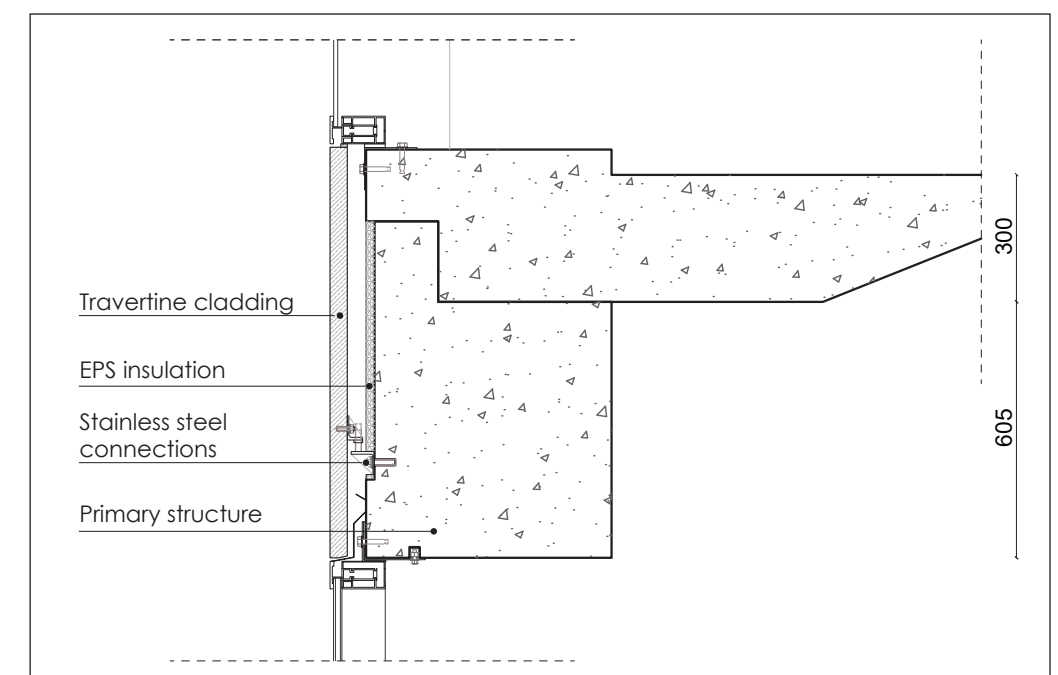

Figure 6.56: Vertical section of the façade of the existing building, Rotterdam Science tower, Rotterdam. Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).

In the existing building, the thermal performance of the façade is extremely poor and it does not comply with current standards (Bouwbesluit). The thermal insulation of the facade is a 20mm-thick layer of EPS, which is penetrated by the metal connectors of the window frames. The insulation line is also interrupted in every floor by the concrete protrusions that support the windows. Regarding the air-tightness, the casing of the windows is not sealed off and as a result, there are high levels of air-leakage through the building envelope (Avdic, Turkcan, Vargas, & Sakthivel, 2018). The façade parameters that are used for the energy simulation of the existing simulation are presented in Table 6.8.

Regarding the energy load (heating, cooling and lighting load), the existing building has a high energy demand, mainly due to the exceedingly high heating load (77.4 kWh/m^2). Figure 6.57 presents the final energy of the existing building (bar 1), the best performing design without considering the energy generated from the BIPVs (bar 2), and the latter considering the energy generated (bar 3). Figure 6.58 presents the same designs and their performance regarding the primary energy. The existing building does not produce any energy, and therefore the primary energy of the existing building is considerably high (53 kWh/m^2). It should be noted that the design does not comply with BENG 2 and BENG 3 requirements. It is also observed that the best performing design with no BIPV panels has a 40% higher final energy value, compared to the same design with the BIPV panels.

Finally, it is noticed that the computational optimization of façade parameters led to 74% improvement of the final energy performance. Additionally, it is proven that using the extended facade area of the high-rise for the production of renewable energy has great potentials for reducing the final energy.

Design	Existing Building	Best Performing Design without BIPV panels	Best Performing Design with BIPV panels
Cooling (kWh/m2)	5.5	9.1	9.1
Heating (kWh/m2)	77.4	22.8	22.8
Lighting (kWh/m2)	11.2	9	9
Energy Generated (kWh/m2)	0	0	16.1
Final Energy (kWh/m2)	94.1	40.9	24.7
Comfort (%)	94.9	99	99
Primary Energy (kWh/m2)	53	29.9	6.6

Table 6.9: Comparison of tested designs regarding energy performance.
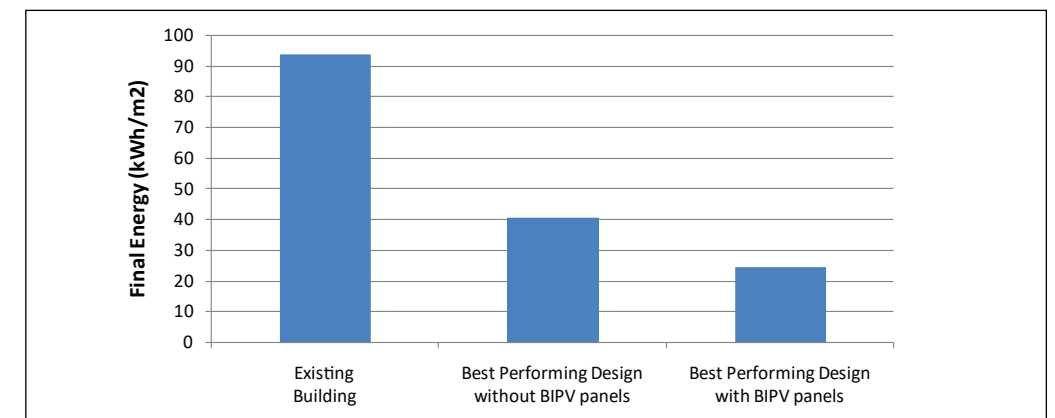
Figure 6.57: Comparison of tested designs regarding the final energy.
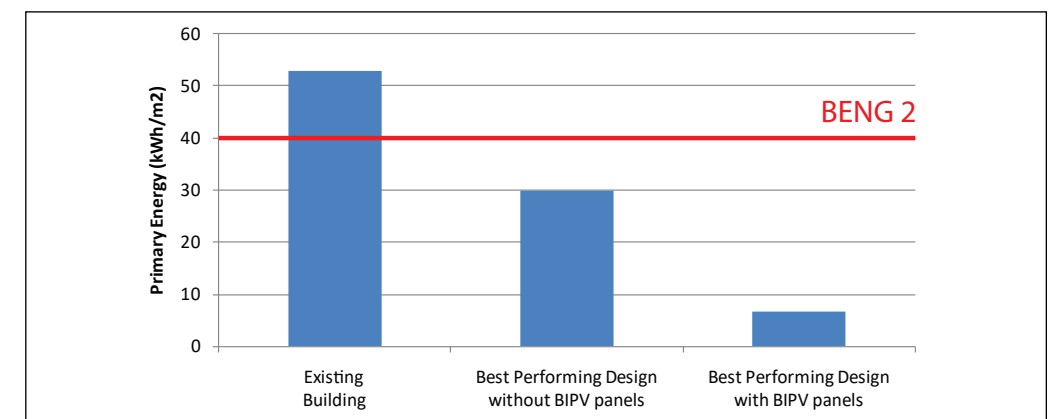
Figure 6.58: Comparison of tested designs regarding the primary energy.

g-value of glazing	0.55
VT-value of glazing	0.5
U-value of glazing (W/m2-K)	3.45
R-value ext.wall (m2-K/W)	1.08
air-tightness (ac/h)	1

Table 6.8: Inputs regarding façade design parameters that were used for the energy simulation of the existing building.

The data for the thermal performance of the façade (U- value of glazing and R-value of exterior wall) was derived from the report of Avdic, Turkcan, Vargas and Sakthivel (2018). Other properties of the façade were collected from the engineering report, from the archive of the municipality of Rotterdam.

07

Façade design proposal
for the reference building

7. Façade design proposal
for the reference building

Based on the results of the optimization, façade design proposals for the reference building, the Rotterdam Science Tower, in Rotterdam, are developed. Following the international style, the existing building features a "flat" façade, with repetitive modular forms; the columns and the spandrel panel on the façade create a vertical and an horizontal grid system (Figures 7.1). Taking into account the strong architectural character of the existing building, the suggested facade designs are developed within these boundaries, as shown below.

Regarding the geometry, the square plan, rotated 45 degrees, is suggested, as that leads to lower final energy levels. The optimization results indicate the w/w ratio just for the tested floors. The ratios for the intermediate floors are calculated as the intermediate values between the tested floors that get higher or lower gradually, resulting in a gradient pattern. Figure 7.2 and 7.3 present façade designs with low w/w ratios, 30-50%, that lead to the lowest values of final energy, among all designs derived from the optimization. Moreover, a façade design proposal with a higher w/w ratio, 60% in all orientations, is also presented.

The inputs (façade design parameters) and the outputs (energy and comfort performance) of each suggested design are reported as well for comparison. The two designs with lower w/w ratios feature a different pattern for the north-east façade, but they lead to similar energy performance levels. That is because the north-east orientation has a weak relationship with the final energy, meaning that the architect has more freedom for designing that elevation. The design with the 60% w/w ratio account for a 15% higher final energy value. The biggest difference is noted regarding, first of all, the energy generated, and secondly, the lighting load, since a higher w/w ratio results in less surface for the BIPV panels, and also higher levels of daylight. It is also observed that the cooling load decreases and the heating load increases when the w/w ratio values increase. A higher w/w ratios allows the extraction of the internal heat gains during summer, but leads to higher heat loss during winter.

Finally, the comparison of the façade designs in parallel with the review of their performance is expected to support the designer during the decision making; the designer can choose among design alternatives based on both soft (e.g. aesthetics), and hard criteria (energy performance).

Figure 7.1: North-east view of the Rotterdam Science tower (ErasmusMC, 2015).

Design 1

Geometry no_5
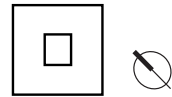
Inputs

R-value ext.wall (m^2-K/W)	5.5
U-value glazing (W/m^2-K)	1.6
g-value glazing	0.3
VT-value glazing	0.7

Outputs

Cooling Load (kWh/m^2)	9.1
Heating Load (kWh/m^2)	22.9
Lighting Load (kWh/m^2)	8.8
Energy Generated (kWh/m^2)	15.9
Final Energy (kWh/m^2)	24.8
Thermal Comfort (%)	99

30%

50%

30%
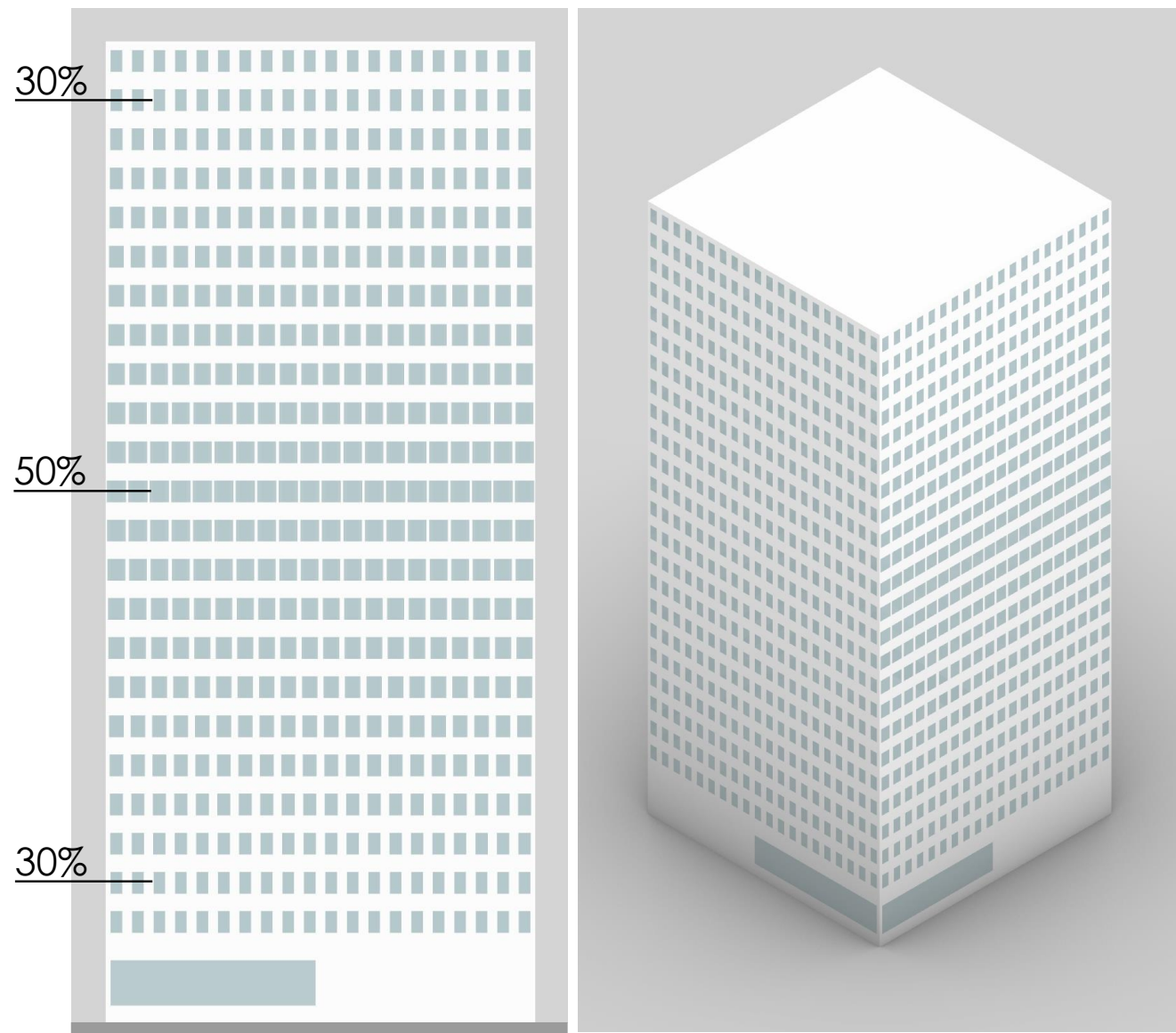
North - East Elevation

Isometric View: East

Figure 7.2: Design 1 - Façade design proposal for the reference building.

Design 2

Geometry no_5
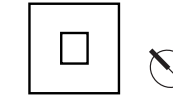
Inputs

R-value ext.wall (m^2-K/W)	5.5
U-value glazing (W/m^2-K)	1.6
g-value glazing	0.3
VT-value glazing	0.7

Outputs

Cooling Load (kWh/m^2)	9.1
Heating Load (kWh/m^2)	22.8
Lighting Load (kWh/m^2)	8.6
Energy Generated (kWh/m^2)	15.8
Final Energy (kWh/m^2)	24.9
Thermal Comfort (%)	99

30%

30%

50%
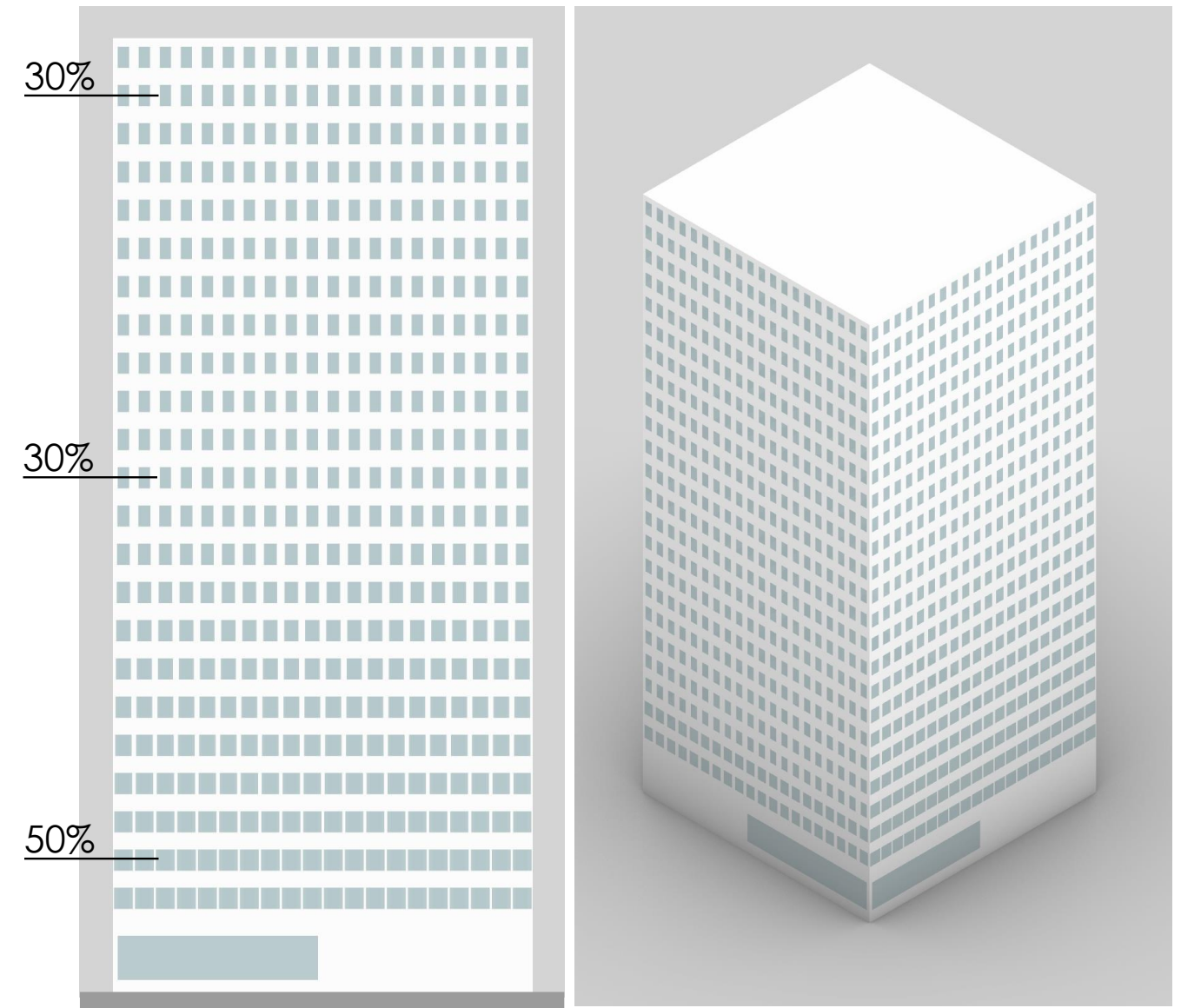
North - East Elevation

Isometric View: East

Figure 7.3: Design 2 - Façade design proposal for the reference building.

Design 3

Geometry no_5
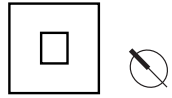
Inputs

R-value ext.wall (m²-K/W)	5.5
U-value glazing (W/m²-K)	1.6
g-value glazing	0.3
VT-value glazing	0.7

Outputs

Cooling Load (kWh/m²)	8.7
Heating Load (kWh/m²)	23.4
Lighting Load (kWh/m²)	6.4
Energy Generated (kWh/m²)	9.4
Final Energy (kWh/m²)	29.1
Thermal Comfort (%)	99

60%

60%

60%

North - East Elevation

Isometric View: East

Figure 7.4: Design 3 - Façade design proposal for the reference building.

8. Guidelines

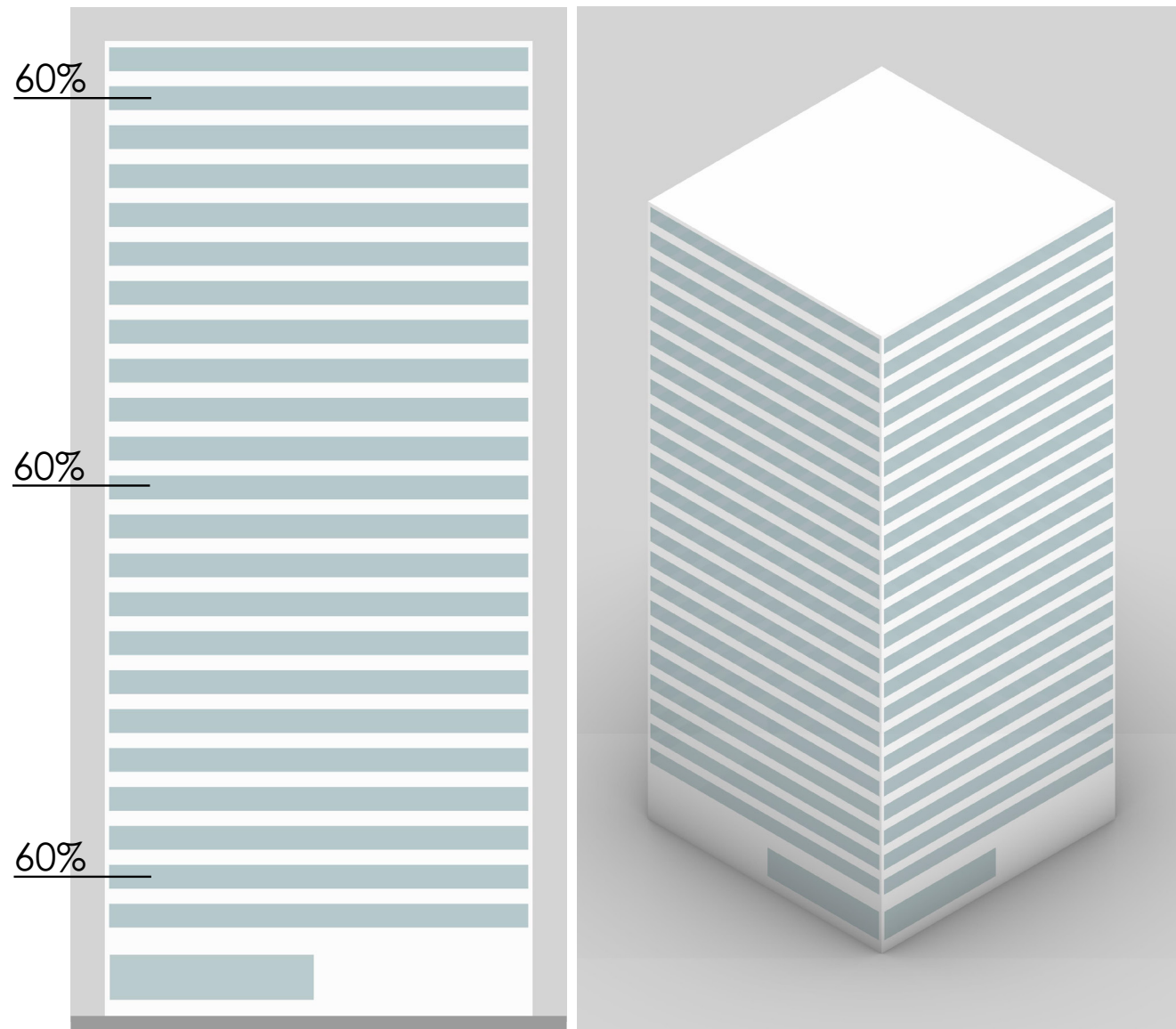The guidelines provide an indication to designers for the façade design of a nearly-zero energy high-rise office building in the temperate climate. They highlight some considerations that need to be set as priorities when aiming at an energy-efficient building, with high thermal comfort levels.

The guidelines are based on the results of the optimization, and more specifically, on the analysis of the effect of the different façade design parameters on the energy performance and the thermal comfort level. The most typical geometry types for offices (rectangular and square), with different orientations, are taken into account for the optimization. Considering the façade design characteristics (w/w ratio, g- value of glazing etc), a range of values are tested per parameter, including the most common values of products to be found in the market, at the time that the research is conducted (Table 8.2). Additionally, the research takes into account the generation of energy with BIPVs, which are mounted on every façade, as a measure to save energy. Table 8.1 summarizes the characteristics of the building, that the guidelines refer to.

The guidelines showcase a general trend for the relationship of different façade design parameters and the building energy performance, as well as the thermal comfort levels. Figures 8.1 - 8.3 present the Pearson Correlation between facade parameters, final energy and thermal comfort. As a synopsis, Figures 8.4 shows the effect of the most influential façade parameters on the energy breakdown and the thermal performance. These charts are followed by a short explanation of the information.

Using the workflow developed in the scope of this study, guidelines for a nearly zero - energy high - rise office building in the temperate climate are established, considering specific façade properties. Since the workflow is developed parametrically, it can facilitate other design cases as well. Following the methodology of the study, the designer can test different variables, according to preference, extract information and establish guidelines for future reference. Setting a wider range of parameters, not only facade parameters, and a wider range of the variables to be tested, the architect is able to customize the design.

▶ **High-rise Office Building**

▶ **Temperate Climate**

▶ **nZEB characteristics**

Connection to the energy grid	On grid		●
	Off grid		
Renewable supply options	On site		●
	Off site		
Energy balance	Period	Annual	●
		Monthly	
	Type	Energy used / Energy Generated	●
		Energy from grid / Energy fed into the grid	
	Unit	Primary Energy	
		Final / Delivered Energy	●
Energy end uses	Building related	Cooling	
		Heating	
		Ventilation	
		Lighting	
	User related	Occupancy	
		Equipment	
	Embodied energy	Not considered	

Table 8.1: Characteristics of the building that the guidelines refer to.

▶ **Facade design parameters**	Tested values
g-value glazing	0.3 / 0.4 / 0.5
VT-value glazing	0.5 / 0.6 / 0.7
U-value glazing (W/m^2-K)	0.8 / 1.2 / 1.6
R-value ext. wall (m^2-K/W)	4.5 / 5.5 / 6.5 / 7.5
w/w (%)	30 / 40 / 50 / 60 / 70 / 80

Table 8.2: Facade design parameters and their range that are taken into account for the establishment of the guidelines

Pearson Correlation between Facade Parameters and Final Energy

-0.691 — Visible transmittance of glazing

-0.459 — U-value of glazing

0.439 — w/w ratio (all orientations)

0.313 — g-value of glazing

0.211 — R-value of exterior wall

Pearson Correlation between w/w ratios and Final Energy

w/w north-east (%) — **0.201**

w/w south-east (%) — **0.626**

w/w south-west (%) — **0.712**

w/w north-west (%) — **0.347**

Pearson Correlation between Facade Parameters and Thermal Comfort

U-value of glazing — **0.762**

Visible transmittance of glazing — **0.499**

-0.758 — g-value of glazing

-0.299 — w/w ratio (all orientations)

-0.159 — R-value of exterior wall

Color scale:
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1

Most influential facade design parameters

g-value of glazing

	Value
Final Energy (kWh/m2)	0.313
Heating Load (kWh/m2)	-0.368
Cooling Load (kWh/m2)	0.357
Thermal Comfort (%)	-0.758

A low g – value of the glazing is suggested in order to meet the thermal comfort requirements. In offices, the internal loads are usually high, which entails the danger of overheating in summer months. Therefore, a low g-value decreases the solar gains, and therefore also the cooling load.

Visible transmittance of glazing

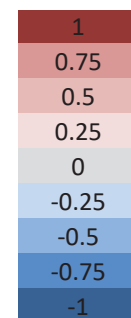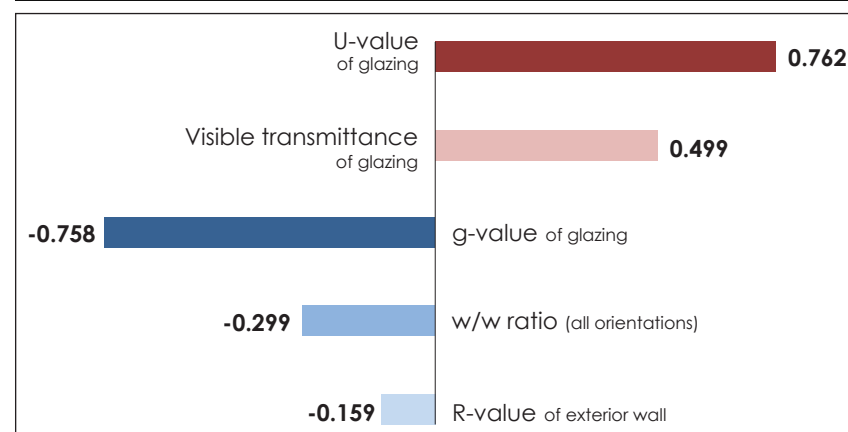|	Value
Final Energy (kWh/m2)	-0.691
Cooling Load (kWh/m2)	-0.529
Lighting Load (kWh/m2)	-0.65

High VT-values are suggested, as they minimize the lighting load which is high for office buildings. The lower values of the lighting load decrease the cooling load during summer as well.

U-value of glazing

	Value
Final Energy (kWh/m2)	-0.459
Cooling Load (kWh/m2)	-0.808
Thermal Comfort (%)	0.762

A high U-value (1.6 W/m²-K) leads to a lower cooling load and a higher comfort level. Due to the great internal loads of the office buildings, a high U - value allows the heat to be extracted from the office space. Considering also low w/w ratio in all façade orientations, the heat loss through the glazing in winter is low, therefore higher U-values are allowed.

w/w ratio North oriented facades

	Value
Final Energy (kWh/m2)	0.626
Heating Load (kWh/m2)	0.004
Cooling Load (kWh/m2)	0.142
Energy Generated (kWh/m2)	-0.696
Thermal Comfort (%)	-0.528

The south oriented façades have the biggest effect on the final energy, as they capture more solar radiation and produce more energy. Therefore, lower values of w/w ratio (30%) are suggested for the south-west and south-east facades. Since north oriented facades do not capture a high amount of radiation, slightly higher w/w ratios are suggested (40-50%)

w/w ratio South oriented facades

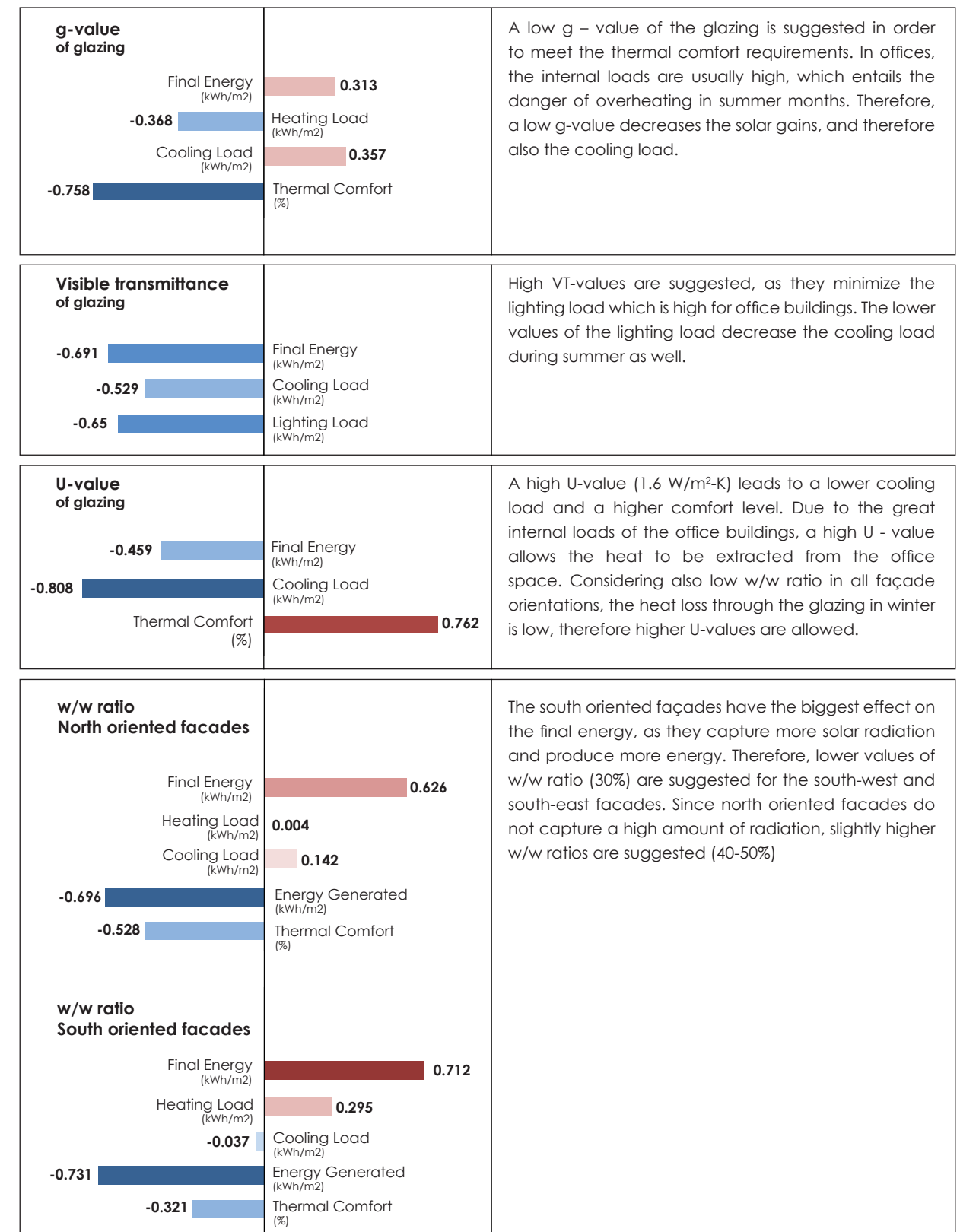|	Value
Final Energy (kWh/m2)	0.712
Heating Load (kWh/m2)	0.295
Cooling Load (kWh/m2)	-0.037
Energy Generated (kWh/m2)	-0.731
Thermal Comfort (%)	-0.321

Figure 8.1: Pearson Correlation between facade parameters and final energy.

Figure 8.2: Pearson correlation between w/w ratios and final energy.

Figure 8.3: Pearson correlation between facade parameters and thermal comfort.

Figure 8.4: Pearson Correlation between the most influential facade parameters, the energy breakdown and the thermal comfort.

09

Potential use-cases
of the developed workflow

9. Potential use-cases
of the developed workflow

Within the timeframe of the research, a workflow is developed, that is used for the extraction of information and the establishment of guidelines for a specific building type and climate. The workflow consists of three main parts: the parametric design, the energy simulation and the optimization / design exploration (Fig.9.1). The workflow is developed parametrically in GH, and as a result, it can be modified or extended, in order to facilitate other uses as well. In general, the workflow can support studies regarding other building types, meaning buildings with different use or building height, and other climates. Furthermore, different design strategies, such as the ventilation strategy or the HVAC system, can be adjusted, according to preference. Hereby, two main suggestions for potential use-cases of the developed workflow are made, as they are expected to be of great importance for the design and construction industry these days. Only a synoptic description of each case is given, as the aim of the examples given below is to highlight the relevance and the applicability of these processes to the scientific and professional framework.

First of all, the research takes into account different technical properties of the façade elements (glazing and exterior wall) and tests combinations of those. Although, in that way, the effect of each parameter on the outputs can be studied, some combinations of parameters could not correspond to products to be found in the market. Therefore, it is suggested to test particular products (such as construction materials) from the market, with specific characteristics, based on the needs of each project. The cost of the products could be another parameter to be taken into account in the optimization. That tool is expected to be applicable for both new buildings and also for the refurbishment of existing buildings.

The example below illustrates the comparison between three glazing products from the market, regarding energy performance and cost (Table 9.1 and Fig.9.2). The specific products were selected by the corresponding list provided by the software DesignBuilder. The list is based on the International Glazing Database version 52 (designbuilder, n.d.). Moreover, these products are selected, based on the results of the optimization: the glazing types have a relatively low solar transmittance value and a relatively high visible-transmittance value. The designer can evaluate the performance of each glazing type, regarding energy performance and cost. Also, the selection of the glazing type is related to the w/w ratio that is preferred for each façade, based on soft criteria (aesthetics) as well. Last but not least, a different glazing type can be suggested according to orientation.
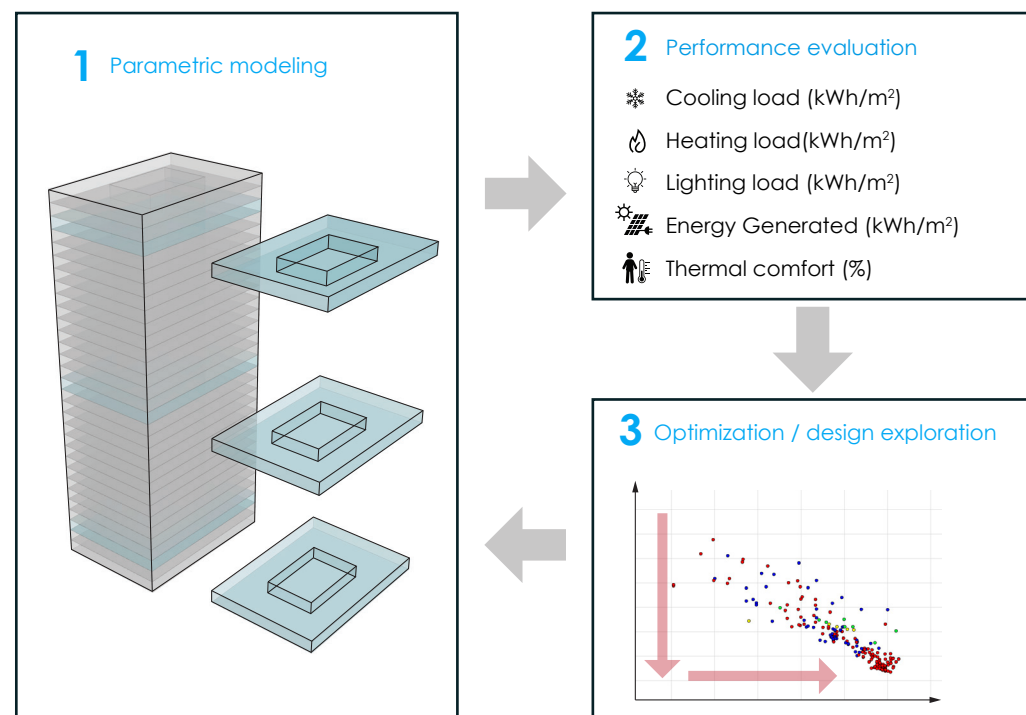

Figure 9.1: The workflow that is developed within the scope of the study includes three main parts: parametric modeling, performance evaluation and optimization/design exploration.

Glazing_no	Name	U-value (W/m2-K)	g-value	VT-value	Cost (E/m2)
0	Dbl LoE (e2=.2) Clr 6mm/13mm Arg	1.689	0.531	0.721	200
1	Dbl LoE Spec Sel Clr 6mm/13mm Arg	1.338	0.345	0.682	200
2	Trp LoE (e5=.1) Clr 3mm/13mm Arg	1.058	0.458	0.698	225

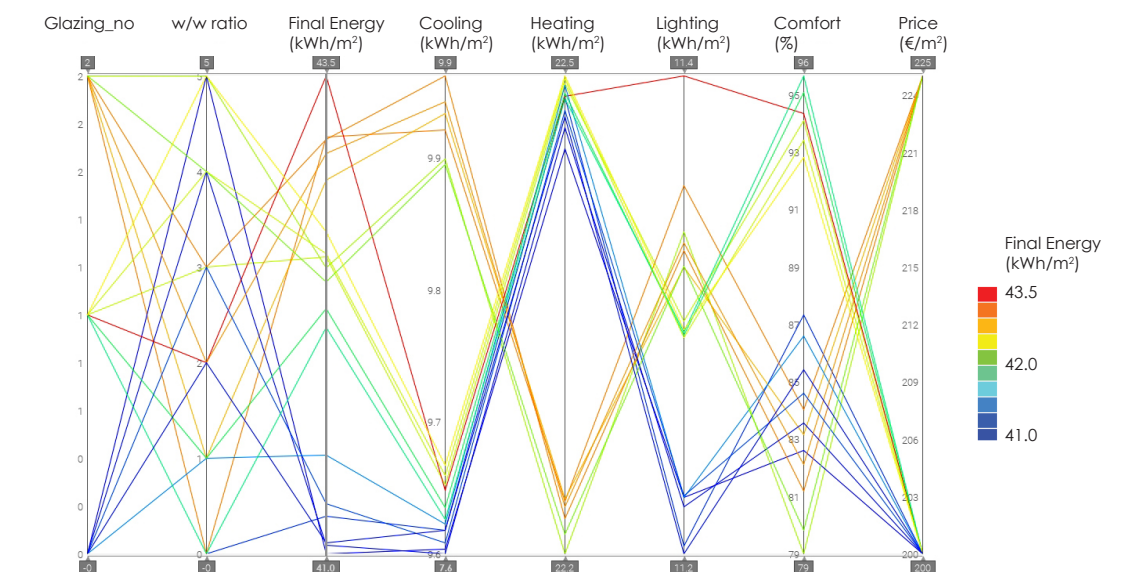Table 9.1: Tested glazing types for the optimization (designbuilder, n.d.).

Figure 9.2: The parallel coordinate chart allows the design exploration of the solution space: the glazing types are evaluated according to energy performance and cost (exported by ModeFRONTIER2018R3).

Secondly, a free-standing building, with no urban context is used as a reference building for the optimization. However, the shading from the nearby buildings is expected to affect considerably the results of the optimization, mainly due to the trends of the energy generated from the BIPV panels. That would also have an effect on the preferable w/w ratios per orientation. As a result, it is suggested to modify the script in GH, in order to include both the geometry of the nearby buildings, and also the materiality of their facades. That tool could be used by architects and/or consultancy companies during the concept phase for the massing and façade parameters optimization. Master plans from the municipality with existing and future buildings would serve as inputs for such studies.

More specifically, regarding the energy generated from BIPV panels, the optimal location and the tilt of the panels could be determined based on the urban context as well, so that the annual renewable energy is maximized. What is more the script should also be modified, in order for the user to choose the area (square meters) of the BIPV panels, based on the cost and the annual yield of them, so that only the façade areas which collect sufficient solar radiation annually are covered with BIPVs. Lastly, the developed workflow used in the research allows the user to test the w/w ratio per floor independently. In addition to that, the differentiation of the w/w ratios and other properties, such as the tilt of the BIPV panels, per "zone" in each floor is considered necessary, taking into account the urban context (Fig.9.3).
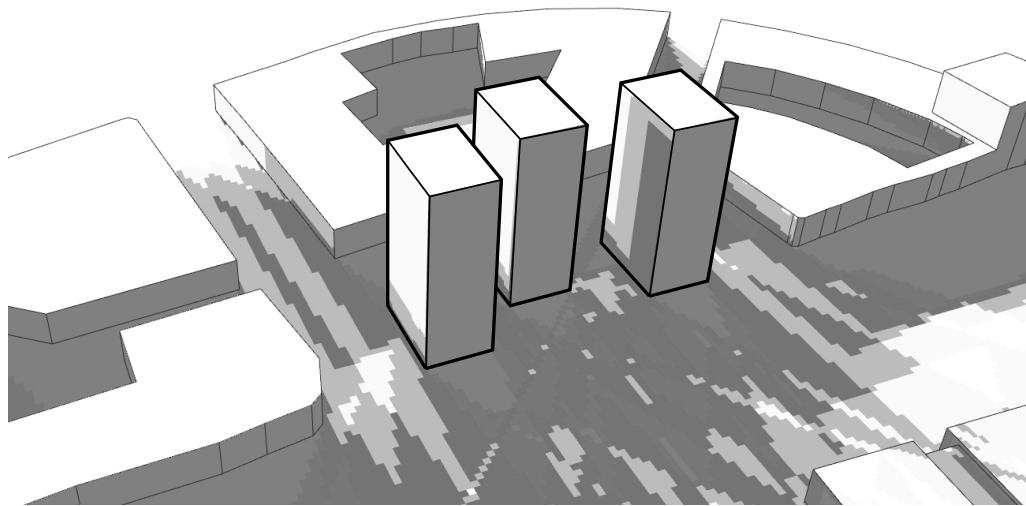

Figure 9.3: Annual shadow analysis of the Rotterdam Science tower, taken into account the urban context (exported by Grasshopper/Ladybug).

10
Conclusions

10. Conclusions

The main objective of the research is to establish guidelines, for early design stages, for the façade design of a nearly Zero - Energy high rise office building in the temperate climate, supported by computational optimization. Based on the results of the optimization, façade design proposals for a reference building are suggested. Within this scope, a methodology is also developed that allows the parametric design and the energy performance evaluation of different façade design alternatives of that type of buildings in the temperate climate.

The literature review conducted for the thesis includes four main categories: nZEBs, energy-efficient high-rise precedents, façade design considerations and computation design. Regulations and initiatives for nZEBs around the world are analyzed. More specifically, regulations for energy-efficient buildings in the Netherlands (BENG and the NVBV Handbook), as well as regulations for the thermal comfort of occupants define the range of the variables of different design façade aspects to be tested in the optimization process.

The review of energy-efficient high-rise office precedents suggest common design strategies to be followed for that climate: double skin façade with dynamic shading in the cavity, mixed-mode ventilation, BMS that controls the operation of the windows, the shading system and the lighting. The analysis of the examples highlights the fact that the multi-disciplinary character of nZEBs requires the investigation of many more aspects, for example natural ventilation strategies, such as the use of atria, and efficient HVAC systems. However, the research focuses on the optimization of façade design parameters, and analyzes their effect on the energy performance of the building. Furthermore, since current regulations for nZEBs require the production of renewable energy, in order to cover part of the primary energy use, the research investigates the potential of BIPVs mounted on the walls of the high-rise building.

Additionally, the advantages of using computational optimization for the automation of the design process are analyzed, putting emphasis on the field of Building Performance Optimization. What is more, the concepts of optimization and design exploration are studied, as the aim of the research is not only to find the best performing designs, but also to understand the effect of the different façade design parameters on the energy and comfort-related performance.

For the optimization study, a typical office building, with repetitive floor plan and open-office layout is used as a reference building. Six different geometry types, regarding shape and orientation, are tested, as these are the most common types for offices to be found in the Netherlands. Three floors, with different building height are used for the simulations. Different façade design parameters are the variables of the optimization, the range of which is indicated by the literature review. A mixed-mode ventilation strategy is applied, and also BIPV panels are mounted on all façade orientations. The outputs of the optimization are the energy demand, the energy generated and the thermal comfort by floor and as total (mean value). The objective of the optimization is to minimize the mean value of the energy demand subtracting the energy generated. The

thermal comfort is set as a constraint for the optimization. Last but not least, the comparison of the results between a well established software (DesignBuilder) and Honeybee evaluates the developed workflow in the latter programme.

The optimization results suggest that the rectangular shape, rotated 45°, performs better compared to the other tested geometries. The second best performing geometry is the rectangular shape, with the long side parallel to the north-south axis. These geometry types have less surface area towards north, which is beneficial for the energy performance of the building. In that way, these designs increase the solar gains and daylight levels. Also, they produce more energy with the BIPVs. Furthermore, low w/w ratios (30%) are suggested for south-oriented facades, and higher ratios (up to 50%) for north-oriented facades. The analysis of the optimization results also shows that the visible transmittance of the glazing has the biggest effect on the energy performance, as high VT-values decrease significantly the lighting load. A slightly high U-value and a low g-value of the glazing are suggested, in order to avoid overheating during summer and also achieve a high thermal comfort level. In addition, the results show that the best performing designs have a high heating load and that they produce a lot of energy. Last but not least, although that the three tested floors have a different building height, they do not show a noticable difference regarding energy performance, which is considered to be due to the high airtightness used for the simulations.

Moreover, the five best performing designs obtained from the optimization are evaluated according to BENG 2 and BENG 3 indicators. The optimal designs perform exceedingly better than the aforementioned requirements, showing that the goal for nearly zero-energy high-rise office buildings is feasible. However, it should be noted that the nearby buildings are not taken into account in the simulations, and BIPV panels are mounted in all facades, which results in high values of energy generated. Additionally, the best performing design is compared with the existing building, in order to quantify the improvement on energy and comfort performance due to the optimization. It is concluded that the computational optimization of façade parameters led to 74% improvement of the final energy performance. It is also proven that the energy generation from the PVs mounted on the facades resulted in 40% reduction of the final energy, indicating the great potential of using the facades of high-rises for production of renewable energy.

What is more, based on the optimization results, façade design proposals for the reference building are suggested. The comparison of the façade designs in parallel with the review of their performance is expected to support the designer during the decision making; the designer can choose among design alternatives based on both soft (e.g. aesthetics), and hard criteria (energy performance).

The optimization results are also used in order to extract guidelines for the façade design of a nearly-zero energy high-rise office building in the temperate climate. The guidelines showcase a general trend for the relationship of different façade design parameters and the building energy performance, as well as the thermal comfort levels. Therefore, they are expected to provide an indication to designers/engineers for the façade design of that kind of buildings. However, for

an holistic approach towards a nZEB, one should also consider other strategies, such as shading and ventilation strategy.

Lastly, the workflow that is developed within the scope of that research allows designers/engineers design parametrically, assess the energy and thermal comfort related performance of the alternatives and optimize different design parameters for nearly zero-energy high-rise offices in the temperate climate. The definition that is developed can be modified and extended, in order to meet the demands for low-rise buildings, other uses (e.g. residential buildings), and even other climates. More specifically, two suggestions for potential use-cases of the workflow are made, due to their relevance and applicability to the scientific and professional framework these days. First of all, it is recommended to test specific products of the market, including cost, and secondly, to incorporate the urban context in the script.

Further work

The study could serve as a starting point for further research. The range of the variables tested in the optimization study could be broadened, in order to take into account other energy-efficient measures, as well.

A dynamic shading system strategy could be incorporated in the developed definition in Honeybee. That study does not take into account dynamic shading, as planned, since daylight simulations with auto-dimming, and dynamic shading are not fully integrated within the energy simulation in Honeybee, at the time that the research is conducted. Dynamic interior shading or shading in the cavity of the double skin façade is expected to minimize considerably the cooling load of high-rise office buildings.

Also, the research focuses only on the optimization of façade design parameters. However, research could be conducted for the optimization of the HVAC system as well, taking into account the energy breakdown of high-rise buildings.

What is more, for that study, the pilOPT optimizer is used, which is a multi-strategy, self-adapting algorithm, using a combination of genetic and gradient-based algorithms. It is suggested to compare the obtained results with those of a brute-force approach, in order to check if the results can be further improved.

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Appendices

BENG requirements (November 2018)

Gebruiksfunctie	Energiebehoefte (BENG 1) [kWh/m².jr]	Primair fossiel energiegebruik (BENG 2)[kWh/m².jr]	Aandeel hernieuwbare energie (BENG 3) [%]
Kantoorfunctie	Indien Als/Ag ≤ 2,2 BENG 1 ≤ 90	≤ 50	≥ 30
	Indien Als/Ag > 2,2 BENG 1 ≤ 90 + 50 * (Als/Ag - 2,2)		

Table a.01.1: BENG requirements announced by NEN in November 2018. Adapted from: (Lente Akkord, 2018).

Open office layout

There are two basic office layouts types: the open office and the private office. The open office category range from the "bull pen" office, where the desks are positioned in rows, to "landscaped" offices or Burolandschaft, where the desks are arranged in different orientations (Brennan, Chugh, & Kline, 2002). Other types of office layouts with no high partition walls include the cubicles and the team clusters. According to the cubicle layout, the workspace is defined, using low partition walls, which are placed accordingly in order to form a "box". The cluster layout suggests grouping teams, in order to promote the communication inside the group (ambient concept, 2018).

Atmospheric properties according to building height

Local Wind Speed Calculation

$$V_Z = V_{met} \cdot \left(\frac{\delta_{met}}{z_{met}} \right)^{\alpha_{met}} \cdot \left(\frac{z}{\delta} \right)^{\alpha} \qquad \text{[Eq.01]}$$

z = altitude, height above ground

V_z = wind speed at altitude z

α = wind speed profile exponent at the site

δ = wind speed profile boundary layer thickness at the site

z_{met} = height above ground of the wind speed sensor at the meteorological station

V_{met} = wind speed measured at the meteorological station

α_{met} = wind speed profile exponent at the meteorological station

δ_{met} = wind speed profile boundary layer thickness at the meteorological station.

The wind speed profile coefficients α, δ, α_{met}, and δ_{met}, are variables that depend on the roughness characteristics of the surrounding terrain.

Outdoor/Exterior Convection

$$Q_c = h_{c,ext} \cdot A \cdot T_{surf} - T_{air} \qquad \text{[Eq.02]}$$

Q_c = rate of exterior convective heat transfer

$h_{c,ext}$ = exterior convection coefficient

A = surface area

Tsurf = surface temperature

Tair = outdoor air temperature

$$h = D + EV_z + FV_z^2 \qquad \text{[Eq.03]}$$

h = heat transfer coefficient

Vz = local wind speed calculated at the height above ground of the surface centroid

D, E, F = material roughness coefficients

(Big Ladder, 2014a)

Glass-Glass-Module: Vision 60P

Technical properties

Module technology	Glass-glass laminate; aluminum frame
Covering material Encapsulation Backing material	Tempered solar glass with anti-refl ective finish, 2 mm EVA-solar cells-EVA, white Tempered glass, 2 mm
Solar cells	60 polycrystalline high power solar cells
Cell dimensions	157 x 157 mm
L x W x H / Weight	$1,680^{\pm 2}$ x $990^{\pm 2}$ x $40^{\pm 0,3}$ mm / appr. 22,8 kg
Connection technology	Cables 2 x 1,0 m/4 mm², TE Connectivity PV4-S-connector
Bypass diodes	3
Max. system voltage	1000 V
Application class	II (acc. to IEC 61730)
Fire class	C (acc. to IEC 61730), E (acc. to EN 13501)
Certifi ed mechanical ratings as per IEC 61215	Suction load up to 2,400 Pa (test load 3,600 Pa) Pressure load up to 5,400 Pa (test load 8,100 Pa)
Recommended stress load as per SOLARWATT Installation Instructions	Please refer to the specifi cations in the Installation Instructions and Warranty Conditions.
Qualifications	IEC 61215 | IEC 61730 (including Protection Class II)

Figure a.01.1: General data for the product Glass-Glass-Module: Vision 60P (solarwatt, n.d.).

STC (Standard Test Conditions): Irradiation intensity 1,000 W/m², spectral distribution AM 1,5 \| Temperature 25±2 °C, in accordance to EN 60904-3

Nominal power P_{max}	275 Wp	280 Wp	285 Wp	290 Wp	295 Wp
Nominal power P_{max}	31,2 V	31,3 V	31,4 V	31,5 V	31,6 V
Nominal current I_{MP}	8,89 A	9,02 A	9,15 A	9,28 A	9,41 A
Open circuit voltage V_{OC}	38,7 V	38,9 V	39,1 V	39,3 V	39,5 V
Short circuit current I_{SC}	9,56 A	9,68 A	9,80 A	9,92 A	10,04 A
Module efficiency	16,7 %	17,0 %	17,3 %	17,6 %	17,9 %

Figure a.01.2: Electrical data (STC) for the product Glass-Glass-Module: Vision 60P (solarwatt, n.d.).

Distribution of designs regarding final energy and energy generated

Geometry type

Figure a.02.1: Ranking of designs based on the geometry type, regarding the final energy and the energy generated (exported by ModeFRONTIER2018R3).

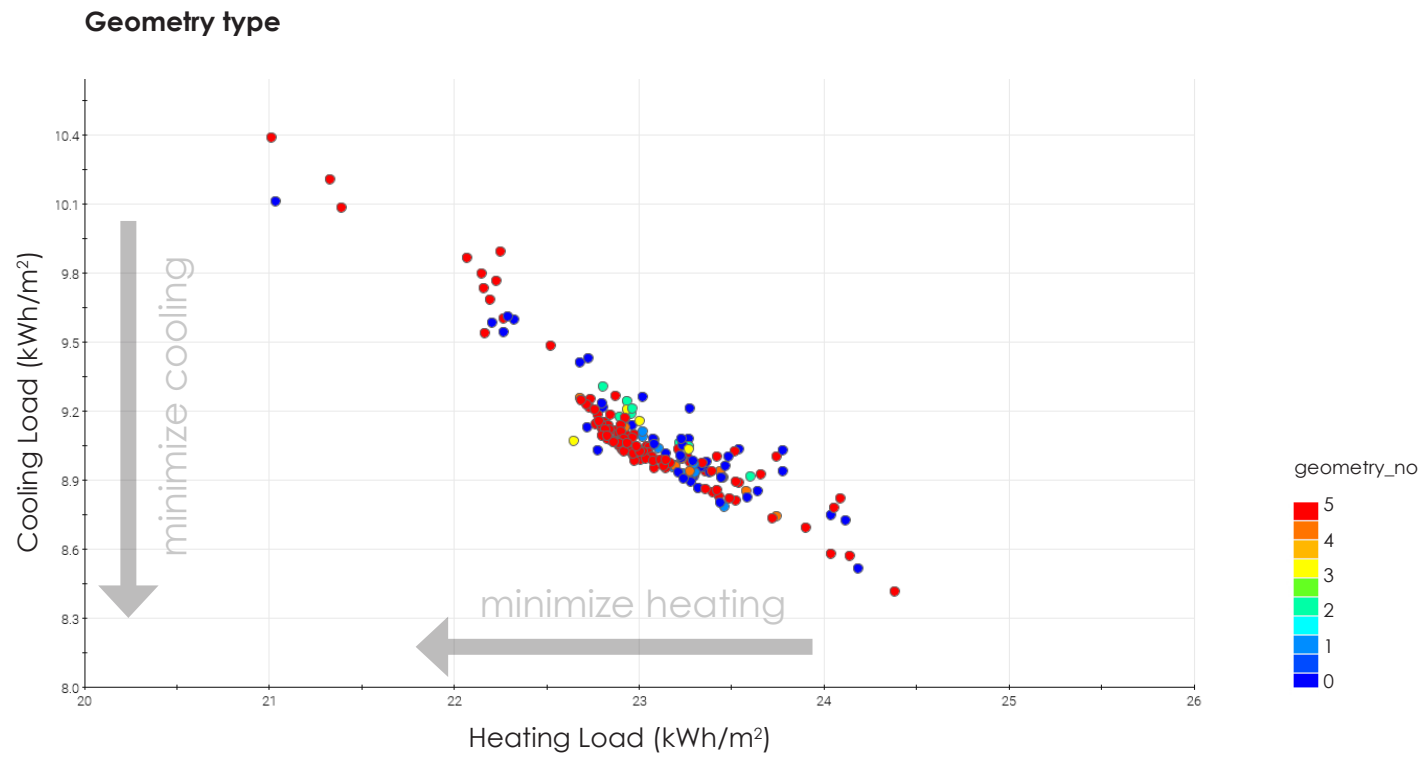# Distribution of designs regarding cooling and heating load

Geometry type

Figure a.02.2: Ranking of designs based on the geometry type, regarding the cooling and heating load (exported by ModeFRONTIER2018R3).
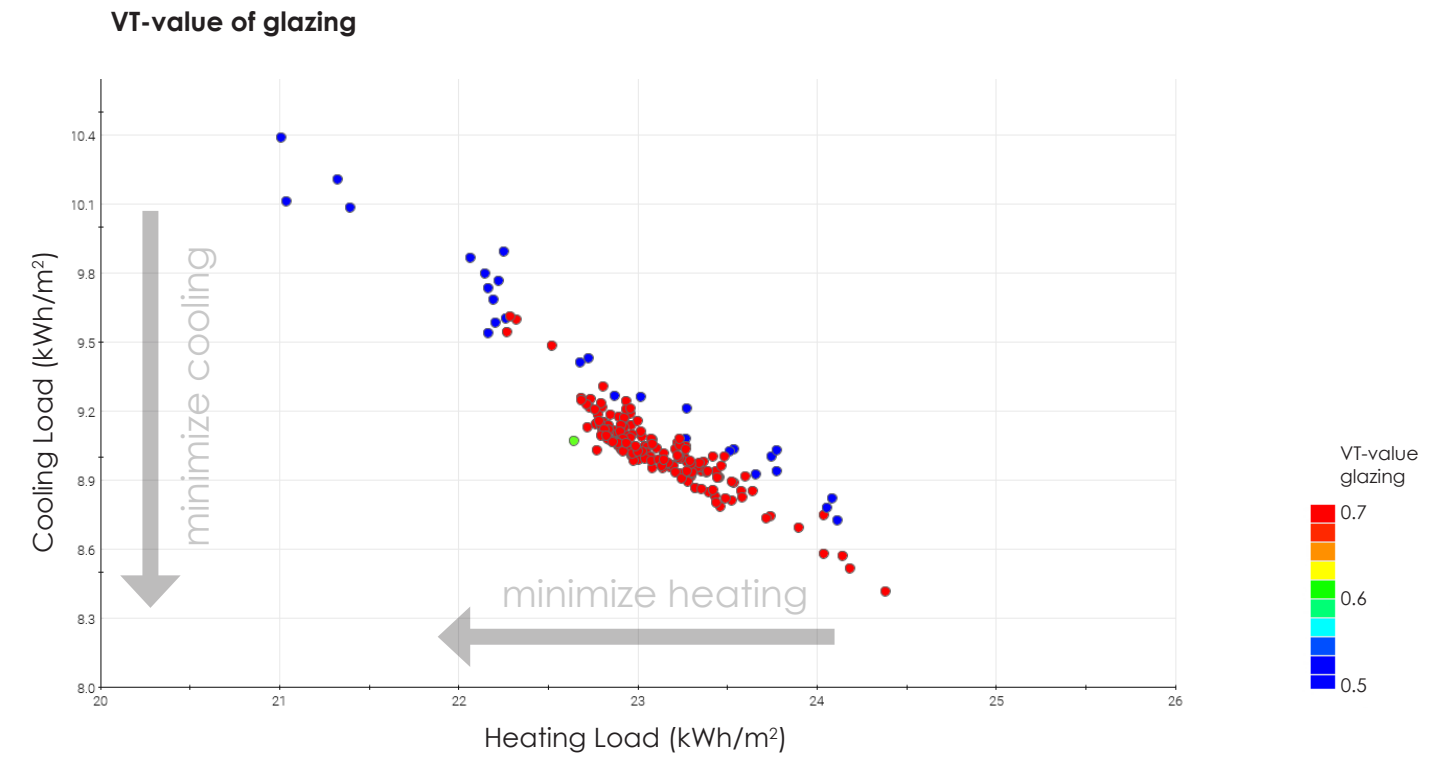
VT-value of glazing

Figure a.02.4: Ranking of designs based on the VT-value of the glazing, regarding the cooling and heating load (exported by ModeFRONTIER2018R3).
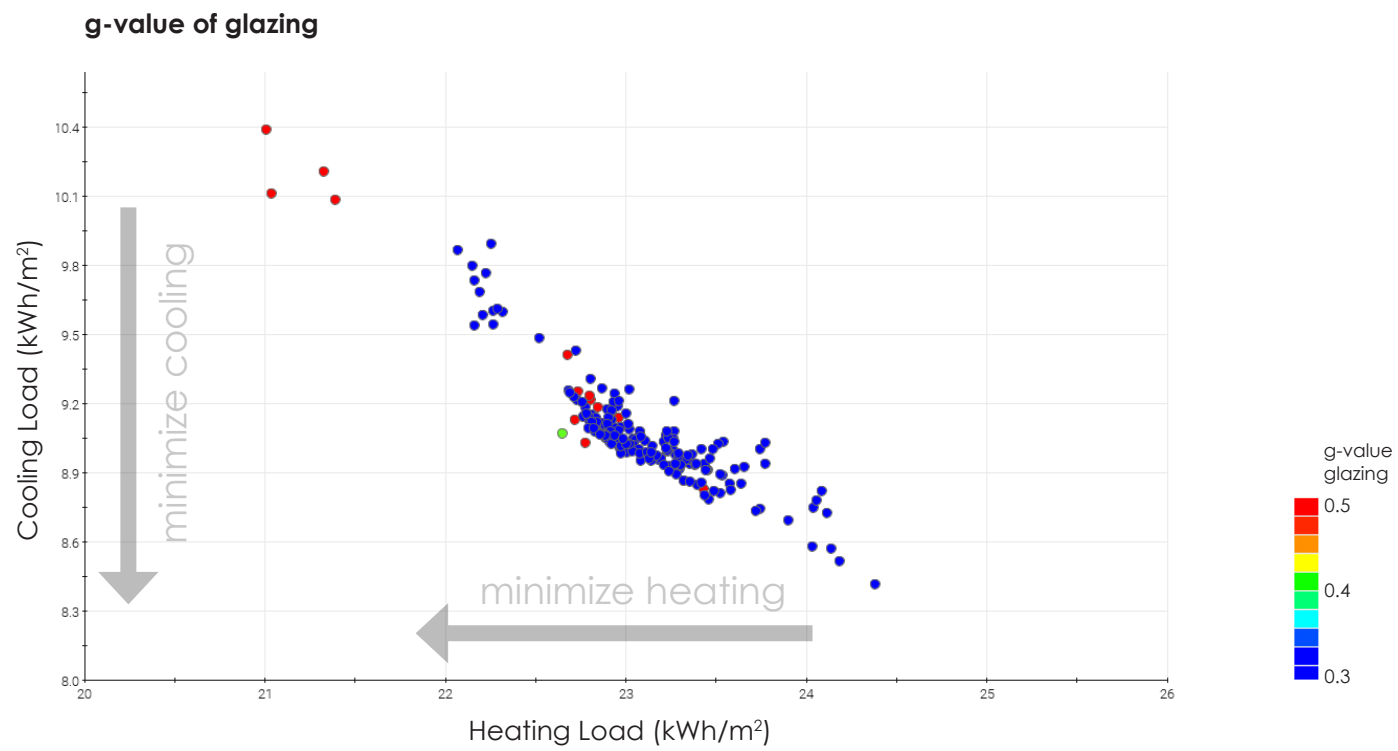
g-value of glazing

Figure a.02.3: Ranking of designs based on the g-value of the glazing, regarding the cooling and heating load (exported by ModeFRONTIER2018R3).
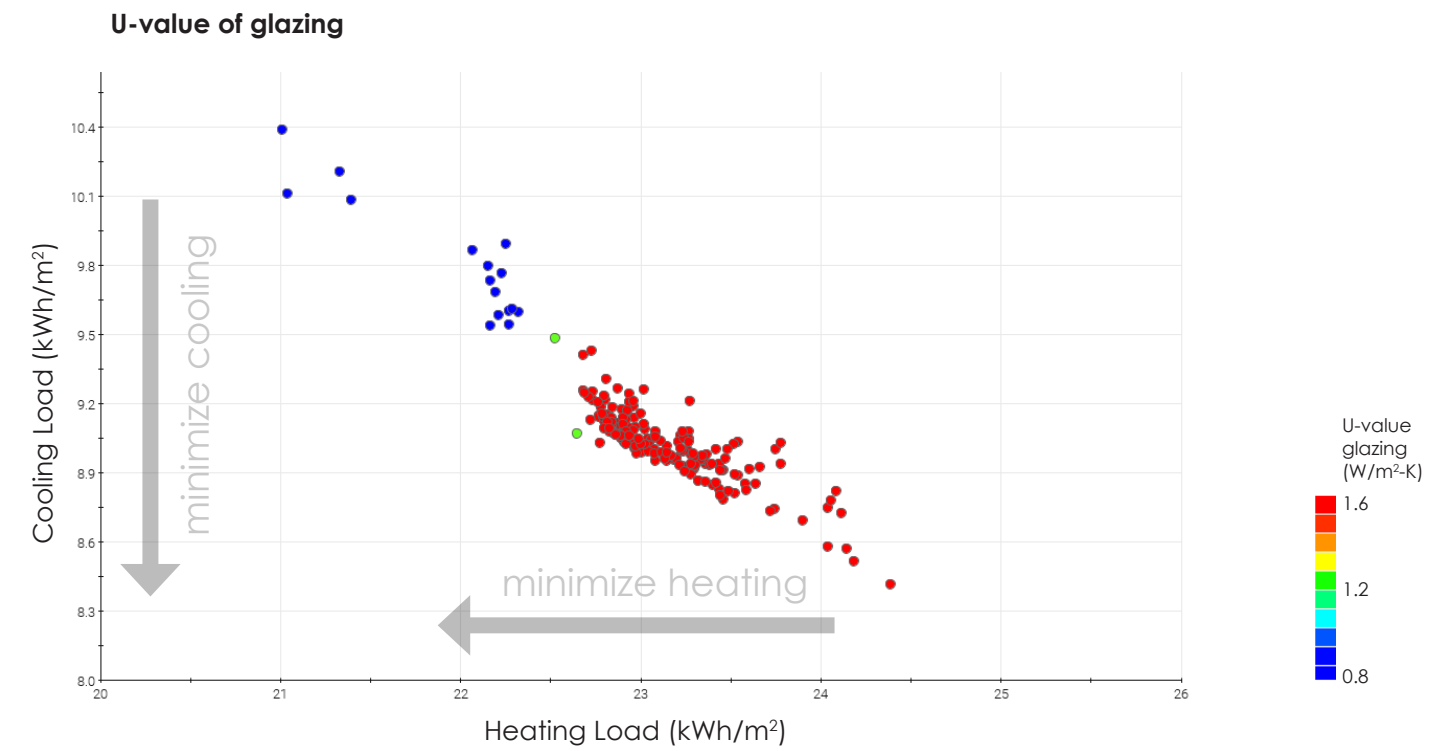
U-value of glazing

Figure a.02.5: Ranking of designs based on the U-value of the glazing, regarding the cooling and heating load (exported by ModeFRONTIER2018R3).

Detailing of the façade, Rotterdam Science tower, Rotterdam

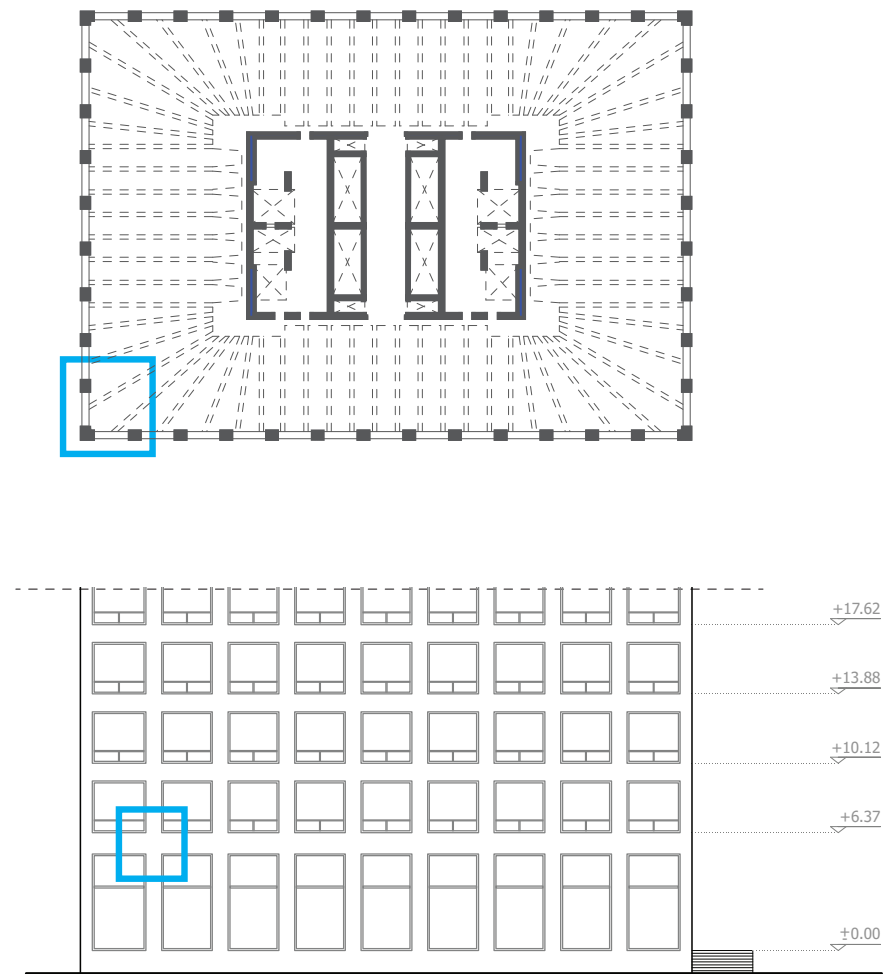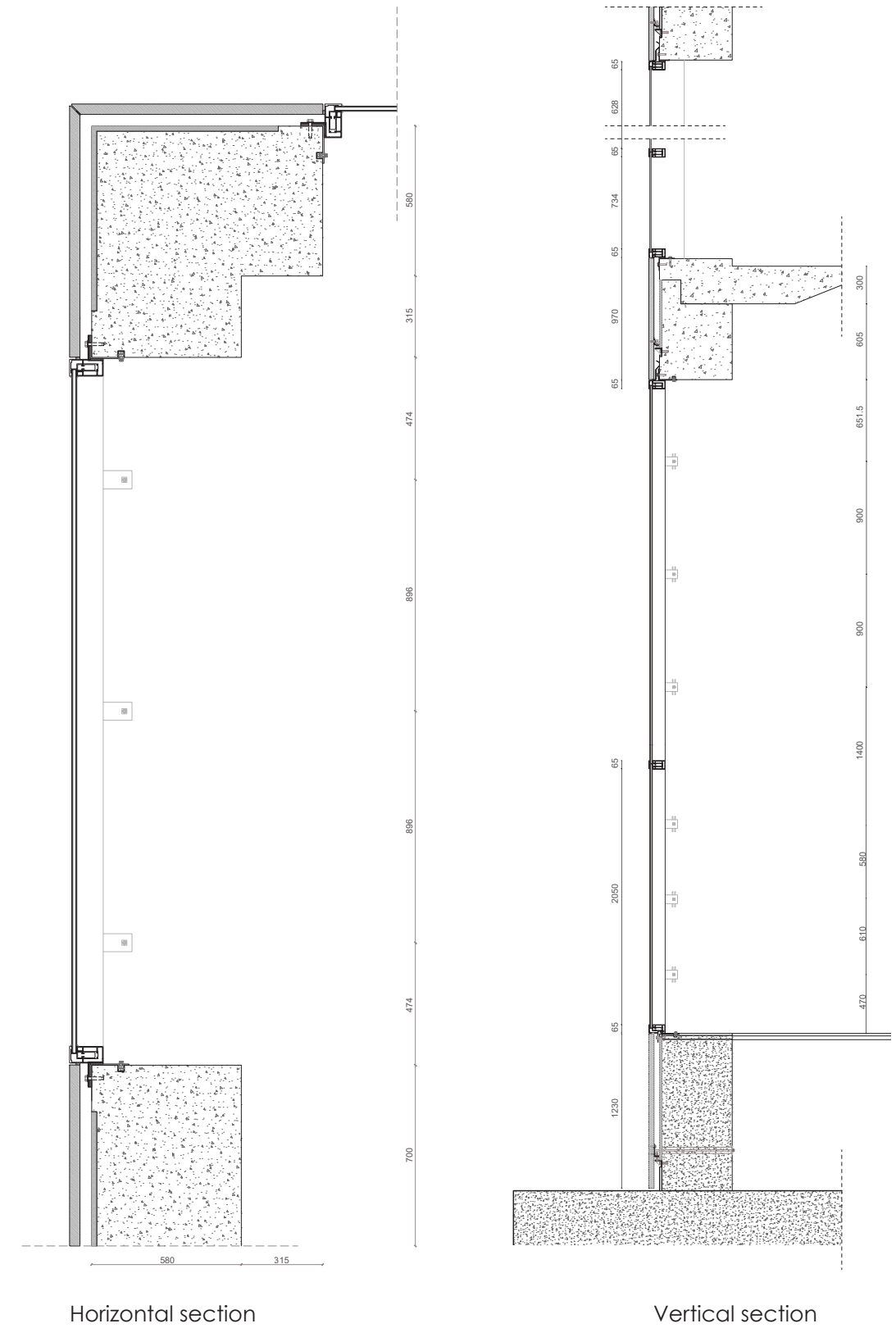Horizontal section

Vertical section

Figure a.03.1 (top): Plan showing the selected fragment for the horizontal section. Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).

Figure a.03.2(below): Elevation showing the selected fragment for the vertical section. Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).

Figure a.03.3(left): Horizontal section of the selected fragment, Rotterdam Science tower, Rotterdam Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).

Figure a.03.4(right): Vertical section of the selected fragment, Rotterdam Science tower, Rotterdam Adapted from: (Avdic, Turkcan, Vargas, & Sakthivel, 2018).