ZERO ENERGY POTENTIAL OF A HIGH RISE OFFICE BUILDING
IN A MEDITERRANEAN CLIMATE

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-Heaven signifies night and day, cold and heat, times and seasons.

-Earth comprises distances, great and small; danger and security; open ground and narrow passes; the chances of life and death.

-If you know the enemy and know yourself, your victory will not stand in doubt; if you know Heaven and know Earth, you may make your victory complete.

Sun Tzu, The Art of War, 5th century B.C.
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ACRONYMS

AC air-conditioning  
BES building energy system  
BPO building performance optimization  
BPS Building Performance Simulation  
BSS building service system  
CCHP combined cooling, heating and power  
CHP Cogeneration Heat and Power  
COP coefficient of performance  
DHW domestic hot water  
EISA Energy Independence and Security Act  
EPC Energy Performance Certificate  
GSHP ground source heat pump  
HVAC Heating, Ventilation and Air Conditioning  
KENAK Κανονισμός Ενεργειακής Απόδοσης Κτιρίων (Regulation for the Energy Efficiency of Buildings)  
LCA life cycle assessment  
NEEAP National Energy Efficiency Action Plan  
NZEB Nearly Zero Energy Buildings  
NZEB Net Zero Energy Buildings  
PCM phase change material  
PV photovoltaic  
REP renewable energy power  
RES renewable energy source  
ZEB Zero Energy Building
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INTRODUCTION

1.1 BACKGROUND

BUILDINGS AND ENERGY

Growth in population, increasing demand for building services and comfort levels, together with increasing time spent inside buildings, indicate that the upward trend in energy demand will continue in the future.

The buildings sector, comprising both the residential and services sub-sectors consumes 35% of the global final energy use (fig. 1.1). It is responsible for about 17% of total direct energy-related CO2 emissions from final energy consumers (International Energy Agency, 2013). If indirect upstream emissions attributable to electricity and heat consumption are taken into account, the sector contributes about one-third of global CO2 emissions. If no action is taken to improve energy efficiency in the buildings sector, energy demand is expected to rise by 50% by 2050. (International Energy Agency, 2013)

Buildings are substantial to the EU’s energy efficiency policy, nearly 40% of final energy consumption and 36% of greenhouse gas emissions is attributed to houses, offices, shops and other buildings. In the U.S.A 48.7% of the energy consumption is attributed to buildings. (Pérez-Lombard, Ortiz and Pout, 2008)

Within the building services sector, the growth in HVAC systems energy use is significant with 50% of building consumption and 20% of total consumption in the USA. (Pérez-Lombard, Ortiz and Pout, 2008)

Currently, space heating and cooling together with water heating are estimated to account for nearly 60% of global energy consumption in buildings. Thus they are the largest opportunity to reduce buildings energy consumption, improve energy security and reduce CO2 emissions, particularly due to the fact that space and water heating provision in some countries is dominated by fossil fuels. Meanwhile, cooling demand is growing rapidly in countries with highly carbon-intensive electricity systems such as China and the United States.

A combination of efficiency standards, extended use of heat pumps, solar thermal and co-generation with waste heat and renewables could reduce growth in electricity demand by 2,000 terawatt-hours (TWh) in 2050. Better use of natural lighting and adoption of more efficient lighting systems, buildings energy consumption for lighting could be reduced by 40% in 2050 compared to current levels. (International Energy Agency, 2013)
Globally, more people live in urban areas than in rural areas, with 54% of the world’s population residing in urban areas in 2014. In 1950, 30% of the world’s population was urban, and by 2050, 66% of the world’s population is projected to be urban. Continuing population growth and urbanization are projected to add 2.5 billion people to the world’s urban population by 2050 (fig. 1.3), with nearly 90% of the increase concentrated in Asia and Africa. (United Nations, Department of Economic and Social Affairs, 2014)

Thus the forthcoming urban environment with higher population densities could offer a reduction on transportation energy. Commuters could need to transport by means of public transportation and thus leading to a more sustainable urban system. Towards this direction, high-rise buildings have a potential in the forthcoming urban growth by hosting these high population densities inside the urban environment and thus limiting the emergence of urban sprawl.

Offices, wholesale & retail trade buildings represent more than 50% of energy use of non-residential buildings in Europe (fig. 1.4). (Buildings Performance Institute Europe 2011)

The increases in the total amount and share of electricity consumed in commercial buildings (fig. 1.5) over the years is consistent with the adoption of new types of electronic equipment and the increased use of existing technologies such as computers and servers, office equipment (printers, copiers, and fax machines), telecommunications equipment, and medical diagnostic and monitoring equipment. In addition to electricity consumed directly by the equipment, many of these electronics require additional cooling, humidity control, and/or ventilation equipment that also increases electricity consumption. (Eia.gov, 2017)
In Greece, a reduction by nearly 50% of energy consumption for heating for offices since 1981 is illustrated in figure 1.6. Office is the second less efficient building type with regard to heating energy consumption after single family buildings. Electricity consumption remained unchanged until 2000 due to low efficiency light lamps used in all the building types. Offices is, regarding the energy consumption for lighting, the second most energy-consuming building type after hospitals (fig. 1.7) and is less efficient than residential and educational buildings.

From the graphs, it is evident that both in Greece and internationally, office buildings are one of the most energy-consuming type of buildings. It can also be concluded that since the 1970s, total consumption in buildings is on the decrease, especially with regard to natural gas consumption. Electricity consumption remains almost stable both in Greece and internationally, due to the technologies that are widely used in buildings.

**ZERO ENERGY BUILDINGS (ZEB)- CURRENT POLICIES**

**THE EUROPEAN FRAMEWORK**

The main legislative instrument for improving the energy efficiency of the European building stock is the European Directive 2002/91/EC on the energy performance of buildings (EPBD) and the EPBD recast (Directive 2010/31/EC). They are part of the EU initiatives on climate change (commitments under the Kyoto Protocol) and security of supply and also part of the EU’s 20-20-20 targets for 2020. (Dascalaki et al., 2012)

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. Additionally, Member States must draw up national plans for increasing the number of NZEBs, which may include targets differentiated according to the category of building. Improving the energy performance of Europe’s building stock is crucial, not only to achieve the EU’s 2020 targets but also to meet the longer term objectives of the climate strategy of the low carbon economy roadmap 2050. (European Comission, 2013)

**THE U.S. TARGETS**

The Energy Independence and Security Act (EISA) 2007 has been promoting the Net-Zero Energy Commercial Building Initiative to help achieve the target of net zero energy for all new commercial buildings by 2030. The zero-energy target is set to 50% for U.S. commercial buildings by 2040 and by 2050 the target is set to net zero for all U.S. commercial buildings. (Marszal et al., 2011)

**THE GREEK NATIONAL FRAMEWORK**

In Greece, the current policy requirement level for implementing regulations for NZEB is voluntary. General guidelines indicate that all primary energy requirements to be covered by renewables and / or CHP, district heating and cooling by 2020 (National target, NEEAP). No standard on NZEB is yet available. (European Comission, 2013)

**THE GREEK TARGET FOR 2016**

Transposition of the directive 2006/32/EC of the european parliament and of the council of 5th April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC took effect in June 2010 by the greek national law N.3855/2010. This lead to the introduction of various energy efficiency improvement measures, energy service companies (ESCOs) and third party financing (TPF) arrangements, in order to achieve by 2016 an overall national indicative target of 9% energy conservation. To reach this target, the overall final energy consumption should be about 19 million ton of oil equivalent (Mtoe) in 2016. Figure 1.8 illustrates the annual final energy consumption for the different end uses from 1960 to 2007 (Dascalaki et al., 2012).

**THE GREEK TARGET FOR 2020**

Transposition of the European Directive 2009/28/EC took effect in June 2010 by the national law N.3851/2010 on RES. This entails that as of 2011 a new building permit requires to reach an annual 60% energy production from solar systems. This entails sanitary hot water (SHW) production from solar thermal systems if technically possible. All public buildings by 2015 and all new buildings by 2020 should cover their primary energy consumption from RES (renewable energy sources), combined heat and power, district or block heating or cooling, and energy efficient heat pumps. In addition, the law N.3851/2010 sets the target by 2020 to reach a contribution of 20% from RES in the national gross final energy consumption, 40% in gross electricity generation and 20% in final energy consumption for heating and cooling (Dascalaki et al., 2012)
THE HELLENIC EPBD LAW (N.3661)

EPBD transposition was implemented in Greece by the national law N.3661/2008 on “Measures for the reduction of energy consumption in buildings and other provisions”. This law is the translation of EPBD, providing the general framework, with all major provisions mandated by the directive.

The new “Regulation on the Energy Performance of Buildings” (KENAK) replaced the existing “Thermal Insulation Regulation” which had been active since 1979. The thermal insulation requirements became stricter and the climatic zoning of the country was modified, increasing the number of climatic zones from 3 to 4. This requirement applies to all new buildings, as well as to existing ones when renovated. For new buildings must be labeled at least energy class B.

The Hellenic regulation (KENAK) outlines the general calculation method and overall approach that is in accordance to European standards, with the main calculation procedure of the building energy demand according to (EN 13790, 2008). It introduces the use of a reference building for benchmarking, the requirements for EPCs (Energy Performance Certificate) based on an asset rating accounting for heating, cooling, ventilation, SHW and lighting, the minimum energy performance requirements and thermal envelope heat loss constraints. Finally, the energy audits of buildings, boiler and heating system inspections and air-conditioning inspections are also briefly elaborated.

Although KENAK is the main regulatory document, it does not elaborate into several technical issues. On the contrary it urges for the development of the necessary technical guidelines in order to be able to provide all the necessary practical information. (Dascalaki et al., 2012)

1.2 PROBLEM STATEMENT

South Europe has a limited number of high-rise buildings compared to the northern part of Europe. Moreover, even smaller is the number of sustainable high-rise buildings especially in the South-eastern part of Europe. Nevertheless, South-eastern Europe’s ports play a crucial role in international trade through shipping, so the potential for the need of office buildings in such kind of locations is increased.

In Greece, standards on NZEB are not available yet and general guidelines for ZEB buildings that derive from the EPBD (Directive 2010/31/EU) of the European Commission can be only implemented voluntarily. The current policies adopted on a national level, refer to new buildings and their technical systems and buildings that undergo extensive renovations, that must meet the minimum energy efficiency requirements set out in the Energy Performance of Buildings Regulation (KENAK).

For the potential of a high-rise building in the hot and dry climate of Greece being zero-energy, limited research has been done. Design strategies and technical knowledge that could lead to more sustainable high-rise office buildings exploiting the high solar radiation potential of southern Europe and tackling the extensive use of air-conditioning and fossil fuels as primary energy source are lacking currently.
1.3 RESEARCH QUESTION

To what extent can the optimization of design and construction parameters lead to a zero energy high-rise office building in the hot-dry climate of Athens, Greece?

SUBQUESTIONS
- What is the most effective combination of parameters that can lead to a potentially zero energy high-rise office building in a hot-dry climate?
- Which parameters have the highest impact on the design of a potentially ZEB high-rise building in a hot-dry climate?
- How do different parameters of the most efficient design strategy influence different aspects of energy demands and thermal comfort in the building?
- How can the optimization resulted parameters be translated in the design of a high-rise office building in Athens, Greece?

1.4 OBJECTIVES

- Define the extent to which a high-rise office building in the hot-dry climate of Athens, Greece can be a zero energy building (ZEB).
- Determine the most effective combination of parameters that could lead to a potentially zero-energy high-rise office building in the hot-dry climate of Athens, Greece.
- Find the most influential parameters in the design of a potentially zero-energy high-rise office building in a hot-dry climate.
- Define the how different parameters of the most efficient design strategy influence different aspects of energy demands and thermal comfort in the building.
- Show how the optimization resulted parameters can be translated in the design of a high-rise office building in Athens, Greece.

1.5 APPROACH AND METHODOLOGY
A starting point for this research is the literature study. This part of the research entails studying scientific papers, journal articles, regulations and existing academic research projects. Subjects that are covered include papers related to design and energy simulation in building constructions, optimization and simulation of the energy performance of buildings, Zero Energy Building strategies, comfort conditions for office spaces, climate and weather data of Athens, passive and active sustainable strategies for designing a ZEB.

Analysis of precedent ZEB examples, ZEB strategies and definitions of high-rise buildings will be used with the aim to define the strategy for implementing the simulation parameters on designing a high-rise office building in Athens. High-rise sustainable buildings like the Torre Agbar, the Bosco Verticale, the 1 Bligh Street, Commerzbank and Post Tower, that are located in temperate or subtropical climates are analyzed for their design and construction parameters that have led to energy reduction. For the design, an existing high-rise building, that is located in the port Piraeus of Athens will be used as a starting point. For further use of this case study in the simulation and optimization process, simplifications and alterations of the building model will be made.

For the energy simulation, construction and geometric parameters will serve as variables and for the energy simulation Grasshopper with Honeybee and Ladybag plug-ins via EnergyPlus will be used. For the optimization process, ModeFRONTIER software connected with Grasshopper will be used. The outputs from the simulation and optimization procedure will be various building designs and constructions, that need to be evaluated. The post processing procedure aims at choosing the most appropriate design and construction according to the objectives of minimizing energy use and maximizing thermal comfort levels set by the design strategy of the building. A sensitivity analysis will be carried with the aid of post-processing tools of ModeFRONTIER, in order to detect the most influential variables and the amount of influence they have on the building’s energy use and thermal comfort levels. This will also help to establish the guidelines for the design of a high-rise open plan office building in Athens, that has reduced energy use and increased thermal comfort.

For the verification of the results from the aforementioned simulation and optimization process, a Design Builder and EnergyPlus simulation will be conducted, in order to detect any deviations between the two software.

The outcome from the evaluation will be used for defining the strategy of designing a high-rise office building in the hot and dry climate of Athens, Greece. Finally, the design of a high-rise office building for the aforementioned location characteristics will be developed.

In order to determine the scope of the research, some boundary conditions are to be established:

- The study refers to high-rise office buildings with repetitive open floor plan.
- The climatic conditions at which the simulations take place are focused on the mediterranean hot and dry climate of Athens, Greece.
- As a starting point, a case study building serves as a design reference for all the optimization steps.
- For the optimization steps of shape and orientation the buildings are simulated with design and construction standards from the current greek regulation for the climatic zone that includes Athens.
- Since grasshopper is used for the 3rd step of optimizations, limitations must be taken into account in the settings for simulation, natural ventilation, daylight, energy generation from photovoltaics, HVAC systems and mixed-mode systems.
- Another limiting factor that dictates the amounts of variable to be calculated is the simulation time. Since more than 1000 designs need to be simulated, accuracy in the grasshopper simulations for daylight and the amount of calculated variables must be compromised.

The increasing urbanization and the need for more sustainable urban systems are issues that are of the utmost importance for future strategic plans and policies. This sustainable direction underlines the importance of developing strategies for zero-energy buildings and zero-energy high-rise buildings. Strategies for a zero-energy building in a hot-dry climate like in Athens could pave the way for policy improvement on nZEBs in similar climates not only in Greece, but also in other countries where similar climatic conditions are applicable.

Furthermore, literature review shows that multi-objective optimizations of energy-consumption and thermal comfort with an integrated approach of passive and active design and construction aspects that could lead to potentially more energy efficient buildings and especially high-rise buildings are currently not widely implemented. By optimizing various design and construction parameters of a high-rise building in the hot and dry mediterranean climate of Athens and integrating both passive and active strategies in the same optimization, could lead to establishing the strategy towards designing a nZEB high-rise office building in Athens. This methodology of defining, optimizing and evaluating the various parameters of designing and constructing a high-rise office building, could be an example for further applications in similar climates in different countries of Europe.
## 1.8 PLANNING ORGANISATION

**WEEKLY WORKING PLAN**

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**P1**
- Background and methodology research
- ZEB / high-rise definition
- Analysis of ZEB procedures
- Comfort considerations
- Define ZEB strategies
- Define building performance simulation
- Define building performance optimization
- Presentation report

**P2**
- Location analysis
- Set-up simulation method
- Building design / simulation / optimization
- Presentation report

**P3**
- Simulation / optimization study
- Evaluation of results
- Design of high-rise office building
- Presentation report

**P4**
- Design of high-rise office building
- Conclusions
- Report
- Presentation

**P5**
2.1 GEOGRAPHY

ATHENS

Athens is the capital and largest city of Greece. Classical Athens was a city state that emerged in conjunction with the seagoing development of the port of Piraeus, which had been a distinct city prior to 5th century B.C.

Athens strategic location in South-eastern Europe has played an important role in expanding in areas like shipping, finance, commerce, international trade and tourism. It is one of the biggest economic centers in southeastern Europe and its port Piraeus is one of the largest passenger ports in the world.

The urban area of Athens (Greater Athens and Greater Piraeus) have a population of 3,090,508 (in 2011) and cover an area of 412km². (Cityofathens.gr, 2017)

PORT OF PIRAEUS

Piraeus is located in the southwest part of the central plain of Attica. It is surrounded by the Mount Aigaleo to the northwest and the Saronic Gulf to the south and west. It is connected with the rest of the Athens Urban Area to the east and northeast. The Piraeus larger urban area includes a central harbor as a hub of commercial and passenger shipping, whereas the two smaller ones cater for recreational and fishing activities.
2.2 CLIMATE

Athens has a hot-summer Mediterranean climate (Köppen-Geiger Csa). The dominant feature of Athens’ climate is alternation between prolonged hot and dry summers and mild to cool winters with moderate rainfall. With an average of 414.1 mm of yearly precipitation (lower than most parts of Greece), rainfall occurs largely between the months of October and April. July and August are the driest months. (Founda, 2011)

Athens is affected by the urban heat island effect in some areas which is caused by human activity, which refers to stone-like and other high thermal mass materials that have replaced the greenery. This leads to altered temperatures compared to the surrounding rural areas and has detrimental effects on energy usage, cooling loads and health. Daily average highs for July (1987-2016) have been measured at 34.4°C. (Founda, 2011)

TEMPERATURE

In the winter, the data indicate temperatures by day reach 14.2°C on average. At night the temperature falls to 7.7°C. In spring temperatures reach 19.7°C generally in the afternoon with overnight lows of 12°C. During summer average high temperatures are 30.5°C and average low temperatures are 21.8°C. Autumn temperatures decrease reaching average highs of 23.4°C during the day and lows of 15.7°C after sunrise. (Athinaig-hellinikon.climatemps.com, 2017)

HUMIDITY

Referring to the relative humidity, Athens registers maximum humidity levels between 80% and 85%. The driest months are June July and August reaching low point of humidity of 25% to 30%. During the winter, relative humidity is the highest (fig.2.2).

PERCIPITATION

The average amount of precipitation for the year in Athens is 365.8 mm. The month with the most precipitation on average is December with 63.5 mm of precipitation. The least precipitation on average occurs in June with an average of 5.1 mm. There are an average on 64.0 days of precipitation, with the most precipitation occurring in December with 11.0 days and the least precipitation occurring in June with 10 days. (En.climate-data.org, 2017)
The highest mean direct normal radiation levels are recorded in the summer months, ranging from 6000 to 7000 Wh/m² per day. In the winter, the direct normal radiation levels fall at approximately 2000 Wh/m² per day.

The new U-values according to KENAK are provided for 4 climate zones based on the heating degree days (HDD) for different locations. According to the previous regulation (TIR) there were 3 climate zones (A–C). KENAK introduced an additional climate zone (D) within the northern regions of the country (zone C). For example, the U-value for external vertical walls in contact with outdoor air was 0.7 W/m²·K with the old regulation (TIR) and is reduced with KENAK by 14–43% (see appendix table a.9). (Ministry of Environment Energy and Climatic Change (MEECC), 2012)

The minimum specifications for the building’s electromechanical (E/M) installations, include heat recovery by at least 50% in central air-handling units with fresh air supply greater than 60%, proper thermal insulation of all heat and cold distribution pipes or ducts, use of outdoor temperature compensation systems, SHW recirculation with variable speed pumps, coverage of the SHW load by 60% from RES, energy efficient lighting with proper central control in nonresidential buildings, thermostatic control in different thermal zones, independent heating and cooling with heat meters, power factor correction in non-residential buildings, etc. (Ministry of Environment Energy and Climatic Change (MEECC), 2012)

The reference building is a carbon copy of the studied (real) building, but it automatically adapts the characteristics of its building elements and E/M installations to meet the minimum energy efficiency requirements. The reference building is a “good” building, (by definition a class-B building). All other building classes for labeling the building are defined as a percentage of the reference building’s primary energy consumption. The building’s ranking is based on the calculated primary annual energy consumption per unit floor area (kWh/m²). (Ministry of Environment Energy and Climatic Change (MEECC), 2012)

TOTEE 20701-1/2010 is the technical report for the calculation of energy building performance and outlines the quasi-steady state monthly calculation procedures and defines the calculation parameters for the energy design study and for facilitating the building energy audits. A software (TEE–KENAK) was developed by the National Observatory of Athens (NOA) for TEE, to support the implementation of KENAK in Greece. For the building’s energy performance assessment, the goal was to develop a common calculation tool that could also be used by commercial software, to avoid inconsistency problems that may arise from using different software that may provide different results. Accordingly, several commercially available software use TEE–KENAK as their core calculation engine and they have been evaluated for compliance. The calculation engine of TEE–KENAK was based on the EPA-NR tool, which was developed within the framework of a European project. (Ministry of Environment Energy and Climatic Change (MEECC), 2012)
NATIONAL APPLICATION OF THE NZEB DEFINITION

The nZEB definition was introduced to national legislation by amendment of the Law 3661 in June 2010 and is identical to the EPBD definition. However, the national NZEB definition has not yet been applied. Due to the lack of the national application of the NZEB definition, it is not possible to identify nZEB buildings in Greece.

REQUIREMENTS FOR TECHNICAL BUILDING SYSTEMS (TBS)

In new buildings and major renovations (in which case the building should have an energy performance rating B after the refurbishment), heating, cooling and lighting installations must fulfill the following requirements (Ministry of Environment Energy and Climatic Change (MEECC), 2012):

- Boilers must be certified with at least a 3-star energy efficiency rating.
- Heat pumps in heating mode must have a COP $\geq 3.2$ if air-cooled and $\geq 4.3$ if water-cooled.
- Heat pumps in cooling mode must have an EER $\geq 2.8$ if air-cooled and $\geq 3.8$ if water-cooled.
- Central (AC) units with a fresh air supply higher than 60% must have a heat recovery ratio of at least 50%.
- Heating/cooling systems must incorporate a weather compensation system.
- Separate thermostatic controls must be installed in each individual heating zone.
- Solar thermal systems must provide 60% of the DHW demand.
- Hot water distribution networks must have an insulation of at least 13 mm thickness and $\lambda \leq 0.04$ W/m*K.
- Air ducts of AC systems must have a minimum of 40 mm insulation with $\lambda \geq 0.04$ W/m*K.
- General lighting systems must have a luminous efficiency of at least 55 lm/W.

For detailed values see tables in appendix.
3.1 ELEMENTS OF B.P.O.

PARAMETRIC SIMULATION

The approach known as ‘parametric simulation method’ can be used to improve building performance. With this method, the input of each variable is varied to see the effect on the design objectives while all other variables are kept constant. This method can be time-consuming while the improvement maybe limited because of a possible conflicting effects of input variables on simulated results. Due to the iterative nature of the procedures, these methods are usually automated by computer programming. Such methods are often known as ‘numerical optimization’ or ‘simulation-based optimization’. (Nguyen, Reiter and Rigo, 2014)

BUILDING PERFORMANCE OPTIMIZATION (B.P.O.)

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OPTIMIZATION VARIABLES

Before conducting an optimization search, first the designer must identify which input variables should be included in the optimization search. Some common variables in BPO studies are either energy related or economic related. (Hamdy, Hasan and Siren, 2013)

OBJECTIVE FUNCTIONS

Optimization is a process that searches for the optimal solution with respect to the objective functions to be maximized or minimized, possibly subjected to some constraints of the dependent variables.

The objective functions are criteria expressed as mathematical functions and are called objective functions. The optimization objectives are to identify for example the cost, energy, comfort levels or environmental impacts of the building. If the optimization problem aims at minimizing a single objective function, it is called single objective optimization problem, otherwise if the objective functions are more than one, it is called multi-objective optimization problem. (Machairas, Tsangrassoulis and Axarli, 2014)

OPTIMIZATION ALGORITHM

The automated optimization is driven by a single or possible combination of optimization algorithms, setting each algorithm to optimize one or more variables.
PARETO OPTIMALITY

Designers can specify their preferences and select the final design. Based on the Pareto front, the designer can aim for aesthetically pleasing buildings while minimizing energy consumption, water use, materials and pollution. Moreover, objectives could include producing sustainable energy, reducing carbon emissions, and improving current energy policies. According to Attia et al. (2013), automated optimization methodologies could prove useful in the late design stages for optimizing control strategies or HVAC systems. The use of optimization can also help by providing information to designers about the effect of variables on simulation results and understanding the relations between variables and objectives. If done manually, this is a time and cost inefficient procedure. Thus, automated simulation based BPO is applied.

Optimization studies are most commonly performed in the early design stage, where the majority of decisions are made. Nevertheless, optimization approaches can also be useful in the late-design stages for optimizing control strategies or HVAC design. Moreover, the use of optimization can also help by providing information to improve current energy policies. According to Attia et al., (2013), automated optimization methodologies could be promoted by the European Commission for calculating cost-optimal levels of minimum energy performance in the EPBD framework.

SINGLE-OBJECTIVE VS MULTI-OBJECTIVE OPTIMIZATION

Optimization can be either single-objective or multi-objective depending on the number of objective functions that define the optimization problem. In a single-objective optimization, an optimum solution of the problem is either its global maximum or minimum. (Attia et al., 2013)

In many real problems, it is required to simultaneously address more than one objective function. Such problems are multi-objective optimization problems. Rather than achieving a solution as a maximum or minimum of a single objective function, the multi-objective optimization, a balanced result should be attained between two or more conflicting objective functions. Therefore, the aim of a multi-objective optimization problem is to find the trade-off in satisfying all the individual objective functions. (Attia et al., 2013)

Architectural design searches often are multi-objective. These objectives could include creating a combination of spaces that meet numerous applicable codes and standards. Moreover, the objectives could be to produce an aesthetically pleasing building while minimizing consumption of energy, water, materials and pollution and simultaneously maximizing the thermal comfort, natural lighting etc. (Shi, 2011) Based on the Pareto front the designer can specify his preferences and select the final design.

PARETO OPTIMALITY

Simulation-based multi-objective optimization methods identify the Pareto optimum trade-off between conflicting design objectives. (Hamdy, Hasan and Siren, 2013) The Pareto frontier is a set of equally optimal solutions, from which a single design solution must be selected. The aim is to find the Pareto optimal trade-off between conflicting design objectives such as for example maximizing thermal comfort and minimizing energy consumption.

A solution is said to be Pareto optimal if, and only if it is not dominated in one or two directions by any other solution, in the decision variable space. (Wang, Rivard and Zmeureanu, 2005) The iterative process of finding a dominant solution eventually results in a set of optimal solutions, also referred to as Pareto front, and each solution is called Pareto optimal. In multi-objective algorithms, when the problem has 2 objectives, the Pareto frontier can be represented as a curve. (Machairas, Tsangrassoulis and Axarli, 2014)

ALGORITHMS USED IN BPO

Most commonly used methods for multi-objective optimizations can be classified into three categories: enumerative algorithms, deterministic algorithms, and stochastic algorithms. (Attia et al., 2013)

According to Attia et al., (2013), the enumerative methods search in a discrete space. These algorithms are computationally expensive and subsequently not appropriate for applications that demand a wide spectrum of solutions.

The deterministic algorithms demand the evaluation functions to have continuity and differentiability. This makes them not suitable for handling discontinuous building and HVAC problems with constrained parameters. (Attia et al., 2013)

On the contrary, the advantage of the stochastic algorithms compared to the aforementioned is the limited mathematical requirements for driving the optimization. (Attia et al., 2013)

Genetic algorithms (GAs) with the Pareto concept have been widely used in recent years for optimization of building and HVAC systems according to Attia et al., (2013). The NSGA-II is a widely used optimization algorithm that handles multi-objective building and HVAC design problems with several variables, with non-linear, discrete and constrained characteristics. (Attia et al., 2013)

TOOLS OF BPO

BPO tools can be classified into the following categories: stand-alone optimization and simulation based optimization tools. Attia et al., (2013) refers to GenOpt, MATLAB, modeFrontier and Topgui as stand-alone optimization tools.

The second category according to Attia et al., (2013) refers to building simulation tools that are driven by feedback from objectives. The most frequently used tools that connect both optimization and simulation techniques are: BeOptTM and Opt-E-PlusTM. (Attia et al., 2013)
modeFRONTIER
Attia et al., (2013) refer to modeFRONTIER as a multidisciplinary software that allows multi-objective optimizations with conflicting objective or not, driven by complex algorithms. ModeFRONTIER can be coupled to various software like: EnergyPlus, ESP-r Fluent, and MATLAB. (Attia et al., 2013) moreover, mode-FRONTIER has extensive post-processing features that allow sophisticated statistical analysis and data visualization. (Attia et al., 2013)

3.2 REVIEW ON OPTIMIZATION STUDIES

Within architectural design the best solution is needed to be found, that satisfies various design criteria. To achieve a sustainable design, performance simulations can be used to verify these criteria and modify the design. The conventional, manual, trial-and-error approach is too time-consuming. Adopting optimization techniques can greatly improve the design efficiency and help designers find the optimal design. The following optimization study review can help define the framework for the optimization study of this Thesis.

-DESIGN OPTIMIZATION OF INSULATION USAGE AND SPACE CONDITIONING LOAD USING ENERGY SIMULATION AND GENETIC ALGORITHM: SHI, X. (2011)

OBJECTIVE
The design objectives are reducing the insulation usage and minimizing the space conditioning load at the same time. The goal was to find a reasonable balance between these two objectives, with the aid of “Pareto frontier” in the decision making phase.

CASE STUDY
The case study is a one-story office building located in Nanjing, China. The building has 3 functional and thermal zones: one conference/training room and two office spaces.

SOFTWARE
ModeFRONTIER was used as the design optimization environment. EnergyPlus was used to simulate the space conditioning load of the building and was integrated into an optimization software tool modeFRONTIER, a multi-objective optimization and design software that can integrate CAD/CAE tools and simulation programs. EnergyPlus was used with RunEPlus batch file. Constraints are provided to the input variables and objectives are defined to guide the algorithm to optimize the design. Since EnergyPlus cannot be directly integrated, it was needed to develop customized codes to link the performance simulation program to the optimization algorithm. The DOS batch file helps creating and specifying directories to run EnergyPlus, and executing EnergyPlus.

OPTIMIZATION ALGORITHM/ STRATEGY
In this study, EPS with a thermal conductivity of 0.03 W/m-K was used on the exterior walls. The variables optimized were actually the thicknesses of the insulation on the six walls.

MOGA (Multi-Objective Genetic Algorithm) a multiple objective search technique which is able to find solutions to optimization was used in this study. MOGA was used because the insulation thickness is discrete in reality such as 20 cm, 25 cm, etc. With MOGA it is convenient to control the number of generations and siblings in each generation and thus the number of designs to be tested.

For the evaluation of the design variables a linear MCDM (Multiple Criteria Decision Making) algorithm named “Savage” offered by modeFRONTIER, was used to perform the iterative process.


OBJECTIVE
In this study global costs (additional investments, replacement costs, energy costs, etc.) are conflicting with delivered primary energy of combinations of compatible energy efficiency and energy supply measures. More than 3×109 combinations are explored.

Stage 1 aims to find the optimal combinations of the design variables that influence the thermal performance (heating, cooling, comfort) of the house: the building-envelope (insulation thickness of external wall, roof, and floor, window type, and building tightness) and the heat-recovery unit.

Stage 2 assesses the primary-energy consumption (PEC) and the life-cycle cost (LCC) of the optimal combinations, addressing the offered primary heating options (e.g., electrical heating, oil boiler, district heating, GSHP).

Stage 3 investigates improving the economical and environmental viability of the optimal combinations of building envelope parameters and HVAC systems. It also includes RESs as supplementary systems for heating and/or electricity production by optimizing the sizes of the systems.

CASE STUDY
A single-family house is chosen as a residential building case study. The simulation time is reduced by using a simplified three-zone model.

SOFTWARE
MATLAB and TRNSYS are used for the simulations.

OPTIMIZATION ALGORITHM/ STRATEGY
To reduce optimization time, a modified multi-objective genetic algorithm PR GA. The algorithm is a combination of deterministic and a controlled elitist GA (a variant of NSGA-II) from MATLAB toolboxes. The modified algorithm is able to address discrete and continuous variables, avoid repetition, keep all the iterations in archive and use them in non-dominated sorting processes.

The GA optimization started with an initial population (20 individuals), including 10 random and 10 manually chosen diverse building-envelope and heat-recovery combinations. GA performed 40 generations, considering all the design variables as discrete.

OBJECTIVE
This paper explores the potential of CABS by using building performance simulation paired with multi-objective optimization and advanced control strategies. The objectives are limited to balancing energy demand and thermal comfort. The objectives to be minimized are the sum of heating and cooling energy demand and the number of hours per year that temperature exceeds 25°C.

Stage 1 was an multi-objective optimization set to find the best performing static building shell designs.

Stage 2 and 3 was investigating the possibility for performance improvement with CABS for a short-term period and a long-term period. The building is optimized for 1 whole year and also separately for 12 months.

CASE STUDY
A two-person perimeter office space (5.4 x 3.6 x 2.7 m) is investigated, according to current Dutch building regulations. The building is only occupied during office hours.

SOFTWARE
TRNSYS was used for the simulations and the optimization was driven by modeFRONTIER (Esteco).

OPTIMIZATION ALGORITHM/ STRATEGY
The non-dominated sorting genetic algorithm II (NSGA-II) was chosen for the process.


OBJECTIVE
The goal was to find a geometry with the lower energy and cost impact. The optimization entails modifying the geometrical variables of 4 parameters: shading device height, width, angle and distance from the wall.

CASE STUDY
In the present paper an office room is investigated, in order to design an optimal fixed shading device. An office room with a floor surface of 20 m² and a south facing window 4.0 m wide and 1.5 m high is investigated. Two different glazing systems have been taken into account, one standard double-glass and a high performance glazing system designed to reduce sun loads. The variables are the solar factor g, solar direct transmittance e, light transmittance, that is the solar radiation transmitted through fenestration weighted with respect to the response of the human eye V and thermal transmittance Ug.

The locations of Trieste and Rome are investigated due to different climatic conditions.

SOFTWARE
The software tool ESP-r was used for calculating thermal loads. DAYSIM for computing illuminance levels. The building’s heating and cooling loads are calculated with the monthly method of EN-ISO 13790. A simulation is carried out with TRNSYS for aboveground and corresponding underground conditions.

OPTIMIZATION ALGORITHM/ STRATEGY
A custom Genetic algorithm GA uses a tournament selection approach for generating Pareto optimal solutions. The generation of the design alternatives is part of the automated process driven by the customized GA-based MOO.

Design parameters are acceptable ranges in values such as building height, number of levels, tapering or twisting factors, and orientation. Construction parameters are quantity of glazing or thermal properties of exterior wall construction.

A customized code for MATLAB is used to generate the tradeoff analysis.


OBJECTIVE
This paper investigates the potential of reducing the energy demand of underground buildings compared to above ground buildings.

CASE STUDY
This study is applied for 15 different climates, 6 building functions and 3 depths, that sums up to 54 different cases. Calculations are made for a single-zone fully underground building. Thus no infiltration or solar gains are present.

SOFTWARE
The building’s heating and cooling loads are calculated with the monthly method of EN-ISO 13790. A simulation is carried out with TRNSYS for aboveground and corresponding underground conditions.

OPTIMIZATION ALGORITHM/ STRATEGY
For starting the optimization, a sample matrix for the input parameters is created by using Latin hypercube sampling (LHS). To analyze the approximate distribution of possible results, the global analysis method Monte Carlo analysis is applied. All inputs are assigned a probability distribution and are varied simultaneously to consider the sensitivity. Finally, a sensitivity analysis identifies the influence of the inputs on the annual energy demand.

Parameters of the study are internal gains, ventilation rate, infiltration rate and ground properties like thermal conductivity, density and specific heat capacity. Construction and design parameters are conductivity of walls, solar transmittance of windows, window to wall ratio and internal heat capacity.

Spearman’s rank correlation is applied for a sensitivity analysis.

OBJECTIVE
The goal is acoustic improvement of open plan office case studies by adaptation of ceiling and wall properties. The objectives are to maximize acoustic performance at places in the room while keeping the amount of added absorption to a minimum.

CASE STUDY
This paper investigates optimizing the acoustic environment of an open plan office.

SOFTWARE
A ray tracer was initially made in Grasshopper. Several models were also exported to CATT-Acoustic for comparison and validation. Finally the Grasshopper script was coupled to Octopus for performing 3 multi-objective optimizations. For both case study buildings a basic geometric model is made in Rhinoceros 5.

OPTIMIZATION ALGORITHM/ STRATEGY
Galapagos included in Grasshopper is used. It is a single-objective evolutionary solver which connects to variable ‘slider’ inputs of a parametric model. Evolutionary algorithms which Galapagos uses are stochastic evolutionary algorithms.

Multi-objective optimization is performed on a parametric model of a case study office. For this purpose the Octopus plugin for Grasshopper is used. Pareto optimal solutions found are at the end compared before the final selection.

CONCLUSIONS
The review of optimization studies has shown that multi-objective problems with many variables need a powerful optimization platform that allows the coupling with a simulation software, but at the same time offers powerful post-processing tools that help the designer visualize the results and make decisions. In several of the aforementioned modeFRONTIER is used as the optimization platform. For the energy simulations, many studied use EnergyPlus and TRNSYS. As it can be concluded from the review of the aforementioned studies, the pairing of a simulation platform and optimization platform most of the time needs the development of custom nodes.

As for driving the optimization, in many building performance optimization studies the non-dominated sorting genetic algorithm NSGA-II is used as it can address discrete variables and can lead in a time-efficient way to a set of pareto optimal solutions.

For this study modeFRONTIER will be used as the optimization platform and the energy simulations will be run with Energy-Plus through Grasshopper, via the plug-ins Honeybee and Ladybug. ModeFRONTIER will be connected with Grasshopper via a custom node/ connection. The non-dominated sorting genetic algorithm NSGA-II will be used to drive the multi-objective optimization for this Thesis. More in depth research on different optimization platforms and optimization algorithms is out of the scope of this graduation Thesis.
4.1 Z.E.B. DEFINITIONS

Historical definitions of zero energy are based mainly on annual energy use for the building’s operation. In the late 70s and early 80s projects related to ‘a zero energy house’, ‘a neutral energy autonomous house’ or ‘an energy-independent house’ regarding energy efficient technologies and passive solutions emerged. That was the era of the oil and fossil fuel resources crisis energy use needed to be restrained. In the literature, different ZEB’s are described and evaluated, but no defined ZEB definition is used. A lack of common understanding of what should be equal to ‘zero’ is detected. It is still unknown if “zero” refer to the energy, the exergy, the CO2 emissions or energy costs. (Marszal et al., 2009)

The lack of a commonly agreed ZEB definition hinders the full integration of the ZEB concept into national building codes and/or international standards. Some countries are closer to including the ZEB concept in their national building codes. The way the zero energy goal is defined, affects the choices designers make to achieve this goal.

Voluntary standards for low-energy buildings using the principles of high insulation, good air tightness and heat recovery ventilation systems such as the scheme R-2000 in Canada, the Passivhaus in Germany, ‘active house’ or ZED in UK serve as precedents for other projects in the world. While those standards are not zero energy nor zero-heating they do achieve reductions in heating energy demand using a practical and cost-efficient approach, but they do not consider thermal comfort properly resulting in issues of overheating in summer.

In current practice, the most common approach to ZEB is to use the electricity grid both as a source and a sink of electricity, thus avoiding on-site electric storage systems. The term ‘net’ is used in grid connected buildings to define the energy balance between energy used and energy sold, the term ‘net-zero energy’ being applied when the balance is zero, usually in an annual period. (Hernandez and Kenny, 2010)

LITERATURE REVIEW

Torcellini, et al. (2006) use the general definition for ZEB given by The U.S. Department of Energy (DOE) Building Technologies Program: “A net zero energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies.”

Torcellini, et al. (2006), distinguish and point out four most commonly used definitions:

-Net Zero Site Energy: A site ZEB produces minimum as much energy as it uses in an annual period, on an on-site basis. Torcellini, et al. (2006)

-Net Zero Source Energy: A source ZEB produces at least the amount of energy that it uses in an annual period, regarding the source energy. Source energy is defined as the primary energy used to generate and transport the energy to the site. In order to calculate the total source energy of a building, the imported and exported energy are multiplied with site-to-source coefficients. Torcellini, et al. (2006)

-Net Zero Energy Costs: In a cost ZEB, the amount of money that the utility service gives to the shareholders of a building for the energy outputs to the grid is equal or more than the money building owners pay the utility service for the energy used in an annual period. Torcellini, et al. (2006)

-Net Zero Energy Emissions: A net-zero emissions building produces the same amount or more of emissions-free renewable energy as it consumes from energy derived from emissions-producing sources. Torcellini, et al. (2006)
Kilikis (2007) highlights that also the exergy of energy should be taken into consideration, since only by using exergy it is possible to assess the complete impact of the building on the environment. Thus, proposes a new definition for the ZEB as:

-Net-Zero Energy Building: a building, that its total annual inputs and outputs that lead to zero exergy, transfer across the building-district boundary and refer to a district energy system and entails the total of electric and other transfer that occurs in a certain period of time. (Marszal et al., 2009)

In many cases the ZEB definition considers only electricity since there is a lack of district heating in many countries. Iqbal, (2004) defines the zero energy home.

-Zero Energy Home: a home that uses commercially available renewable energy technology with energy efficient construction. This home consumes no fossil fuels and its electricity consumption is equal to the electricity production on an annual basis. The zero energy home can be either grid connected or not. (Marszal et al., 2011)

The operating energy demand is not the sole focus of all ZEB buildings, but also the energy embodied in materials and construction play an important role. One example of such a project can be BedZED- neutral carbon eco-community near London. Morbitzer, (2008) indicates the definition of the BedZED.

-BedZED: is built from natural, recycled or reclaimed materials. The wood that is used derives from sustainable sources, and construction materials must have low embodied energy and acquired possibly within 35-miles from the site location. (Marszal et al., 2009)

In the International Energy Agency (IEA) report Jens Laustsen (2008) presents a general definition for a ZEB: Zero Energy Buildings only get all their required energy from solar energy and other renewable energy sources. When focusing on the issue of what zero refers to Laustsen, (2008), 2 definitions:

-Zero Net Energy Buildings: They annually deliver the same amount of energy to the supply grids as they use from the grids. Thus, fossil fuels are not needed for the building uses. (Marszal et al., 2011)

-Zero Carbon Buildings: They do not use energy that derives from carbon dioxide emission procedures in an annual period. Buildings can be considered carbon neutral or even positive, if they produce the required amount of CO2 free energy to supply themselves. Zero Carbon Buildings differ from Zero Energy Building because they can use CO2 free sources, like windmills, nuclear power and PV solar systems outside the building’s site. (Marszal et al., 2011)

The U.S. Department of Energy (2015) defines a Zero Energy Building (ZEB) as:

-Zero Energy Building: is an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy. (U.S. Department of Energy, 2015)

The U.S. Department of Energy also adds the definition of the site boundary for a Zero Energy Building (ZEB) as:

-site boundary for a Zero Energy Building: This boundary could be around the building footprint if the on-site renewable energy is located within the building footprint, or around the building site if some of the on-site renewable energy is on-site but not within the building footprint. Delivered energy and exported energy are measured at the site boundary. (U.S. Department of Energy, 2015)

The site boundary for a Zero Energy Campus allows for the building sites on a campus to be aggregated so that the combined on-site renewable energy could offset the combined building energy from the buildings on the campus. The site boundary for a Zero Energy Community would allow a group of project sites at different locations to be aggregated so that the combined on-site renewable energy could offset the combined building energy from the aggregated project sites. Zero Energy Communities can share the benefit of renewable energy projects. (U.S. Department of Energy, 2015)
THE EUROPEAN DEFINITION: EPBD (ENERGY PERFORMANCE OF BUILDINGS’ DIRECTIVE)

The European Parliament has issued a recast of the Energy Performance of Buildings Directive where the nearly-zero energy building is defined as a building where, “as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site” (Hernandez and Kenny, 2010, pp. 817).

The energy performance of a building means 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.

The directive requires nearly zero energy buildings and is aided by the calculation framework EN15603. In the definition, local conditions should be taken into account, but the uniform methodology can be used by all Member States. The directive defines a nearly zero energy building as a building that has a very high energy performance. It also requires the calculation of a primary energy indicator. The nearly zero energy required should be covered by energy from renewable sources on-site or nearby. (Kurnitski et al., 2011)

Based on the directive’s definition, nearly zero energy building is technically defined through the net zero energy building, which is a building using 0 kWh/(m² a) primary energy. Following the cost-optimality principle of the directive, nearly net zero energy building definition is proposed as national cost optimal energy use of > 0 kWh/(m² a) primary energy. For the uniform methodology, a general system boundary definition was established with the following definitions (Kurnitski et al., 2011):

- **net Zero Energy Building (nZEB):** energy use of 0 kWh/(m² a) primary energy
- **nearly net Zero Energy Building (nnZEB):** national cost optimal energy use of > 0 kWh/(m² a) primary energy
- **energy Performance of the building:** calculated or measured amount of energy delivered and exported actually used or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alia, energy used for heating, cooling, ventilation, domestic hot water, lighting and appliances.
- **delivered energy:** energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (e.g., heating, cooling, ventilation, domestic hot water, lighting and appliances)
- **exported energy:** energy, expressed per energy carrier, delivered by the technical building systems through the system boundary and used outside the system boundary
- **net delivered energy:** delivered minus exported energy, both expressed per energy carrier
- **primary energy:** energy from renewable and non-renewable sources which has not undergone any conversion or transformation process
- **primary energy factor:** the primary energy factor accounts for the extraction of the energy carrier and its transport to the utilization site, as well as processing, storage, generation, transmission, distribution, and delivery.
- **CO2 emission coefficient:** for a given energy carrier, quantity of CO2 emitted to atmosphere per unit of delivered energy
- **system boundary:** boundary that includes all areas associated with the building (both inside and outside of the building) where energy is used or produced

THE U.S. DEFINITION: ASHRAE DEFINITION

The ASHRAE Vision 2020 (ASHRAE, 2008) entails definitions that refer to the ASHRAE code and have application at the building sector of the U.S. The following definitions are part of the ASHRAE Vision 2020:

- **net zero site energy building:** produces as much energy as it uses when measured inside the site boundary. Applying this definition is useful because verification can be achieved through on-site metering, but it does not distinguish between fuel types or account for inefficiencies in the utility grid.
- **net zero source energy building:** produces as much energy as it uses compared to the energy content at the source. The system boundary is drawn around the building, the transmission system, the power plant, and the energy consumed in getting the fuel source to the power plant. This reflects a wider total energy impact compared to a site definition. The challenges, however, occur by the difficulties in acquiring site-to-source conversions and by the limitations of these conversions. (ASHRAE, 2008)

Building owners are typically most interested in net zero energy cost buildings because they tend to use energy efficiency and renewable energy as part of their business plan.

- **net zero energy cost buildings:** this definition, like the site NZEB definition, is easy to verify with utility bills. Market forces provide a good balance between fuel types based on fuel availability. Costs also tend to include the impact of the infrastructure. Getting to zero, however, may be difficult due to themselves utility rate structures. Many rate structures will give credit for energy returned to the grid but will not allow this number to go below zero on an annual basis. As a result, there is no way to recover costs incurred by fixed and demand charges. (ASHRAE, 2008)
- **net zero energy emissions building:** looks at the emissions that were produced by the energy needs of the building. This is probably a better model for “green” energy sources; however, like the source NZEB definition, it can be difficult to calculate. (ASHRAE, 2008)
There is still a need to create a single definition, however. Without this, there is a questions as to whether a building can be universally considered a NZEB. For the calculation method site energy measurements have been chosen through an agreement of understanding between ASHRAE, the American Institute of Architects (AIA), the U.S. Green Building Council (USGBC), and the Illuminating Engineering Society of North America (IESNA). (ASHRAE, 2008)

NATIONAL ZEB DEFINITION FOR GREECE

The nZEB definition was introduced to national legislation by amendment of the Law 3661 in June 2010 and is identical to the EPBD definition. However, the national nZEB definition has not yet been applied. Due to the lack of the national application of the nZEB definition, it is not possible to identify nZEB buildings.

4.2 Z.E.B. CHARACTERISTICS

There are various definitions for a ‘zero energy’ and a ‘net-zero’ energy building. Within the built environment the term ‘net energy’ is often used to describe a balance between energy used by the building, its occupants and systems and energy produced by its renewable energy systems. From the aforementioned definitions, certain categories of ZEB characteristics derive.

CONNECTION TO THE ENERGY GRID

The off-grid ZEBs are considered as a step towards grid connected, net ZEBs. (Marszal et al., 2011)

OFF-GRID ZEB

The off-grid ZEB also named ‘self-sufficient’, ‘autonomous’ or ‘stand alone’ is not connected to any utility grid and hence needs to use some heat and electricity storage systems for periods with peak loads (Marszal et al., 2012). A definition for off-grid ZEBs was written by Laustsen (2008) for the International Energy Agency (IEA) : a Zero Stand Alone Building does not need any connection to the grid but may need it only for safety reasons. Stand alone buildings can store energy for and use it in the night or in winter and thus are autonomous. (Marszal et al., 2012)

The off-grid ZEB can hardly refer to a broader spectrum of society globally due to many issues like the need for large storage, backup generators, energy losses due to conversions and much space required for renewable energy producing systems. Vale and Vale, (2000) indicate that in the United Kingdom, which is densely populated and has an advanced national electricity grid, it would make no sense to discard the existing grid, and replace it with energy storage systems for off-grid buildings. (Marszal et al., 2012)

ON-GRID ZEB

The difference between an off-grid ZEB and an on grid ZEB is that, the off-grid ZEB does not have any connection to the grid. An on-grid ZEB is a building that produces energy, with the possibility for purchasing energy from the grid and feeding it back to it. (Marszal et al., 2012)

The on-grid ZEB or ‘grid connected’ or ‘net zero energy’, can be connected to several energy infrastructures such as an electricity grid, district heating and cooling system, gas, biomass and biofuels network. Thus, it is possible to purchase and feed energy from and to the grid so as to avoid energy storage. According to Laustsen (2008) a grid connected ZEB definition is: ‘Zero Net Energy Building that annually deliver the same amount of energy to the grid as they consume from it. That means that fossil fuels are not needed for heating, cooling, lighting. (Marszal et al., 2012)

RENEWABLE ENERGY SUPPLY OPTIONS

The renewable sources can be located on the site (sun, wind) or need to be delivered on site (biomass, sun, wind). Thus, 2 renewable energy supply options exist, the on-site supply and the off-site supply. Various supply-side renewable energy technologies are available for ZEBs. Typical examples of technologies available today include PV, solar hot water, wind, hydroelectric, and biofuels. (Torcellini, Piess and Deru, 2006)

According to the EPBD recast: ‘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’. (Marszal 2012, pp.974)
There is still a need to create a single definition, however. Without this, there is a questions as to whether a building can be universally considered a NZEB. For the calculation method site energy measurements have been chosen through an agreement of understanding between ASHRAE, the American Institute of Architects (AIA), the U.S. Green Building Council (USGBC), and the Illuminating Engineering Society of North America (IESNA). (ASHRAE, 2008)

ON-SITE
For the on-site supply there is a distinction between the building footprint the site on which the building is located. (Marszal et al., 2012)

Determining a project’s boundary, which can be substantially larger than the building footprint, is an important part of defining on-site generation sources. The question arises as to whether this larger area should be considered for on-site renewable energy production. Typically, the only area available for on-site energy production that a building has guaranteed as “its own” over its lifetime is within its footprint. (Torcellini, Pless and Deru, 2006)

Sometimes it is not clear whether, biomass/biofuel CHP can be considered as on-site, since electricity is generated on-site with the aid of these fuels or can be considered off-site renewable supply since the biomass of biofuel derive from sources out of the building’s site. (Marszal et al., 2012)

<table>
<thead>
<tr>
<th>ON-SITE SUPPLY OPTIONS</th>
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<tbody>
<tr>
<td>1 Use renewable energy sources available within the building's footprint</td>
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<tr>
<td>2 Use renewable energy sources available at the site</td>
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Figure 4.4: ZEB Renewable Supply Options
Source: Torcellini, Pless and Deru, 2006

OFF-SITE
Regarding the off-site energy supply, the building can use renewable energy sources available off-site in order to produce energy on-site. An other way is to purchase energy from off-site renewable energy sources. (Torcellini, Pless and Deru, 2006)

Renewable sources imported to the site, such as wood pellets, ethanol, or biodiesel count as on-site renewable sources (fig. 4.5). Biofuels such as waste vegetable oil from waste streams and methane from human and animal wastes can also be valuable energy sources, but these materials are typically imported for the on-site process. The final option for supply-side renewable energy sources includes purchasing “green credits” or renewable sources such as wind power or utility PV systems that are available to the electrical grid. These central resources require infrastructure to move the energy to the building and are not always available. (Torcellini, Pless and Deru, 2006)

Taking into consideration the limited area of roof and/or façade, primarily in the dense city areas, the weather conditions of northern Europe, the growing interest and number of wind turbine infrastructures, the off-site renewable energy supply options could become a meaningful solution for reaching the ‘zero’ energy goal. (Torcellini et al., 2012)

<table>
<thead>
<tr>
<th>OFF-SITE SUPPLY OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Use renewable energy sources available off site to generate energy on site</td>
</tr>
<tr>
<td>2 Purchase off-site renewable energy sources</td>
</tr>
</tbody>
</table>

Figure 4.5: ZEB Renewable Energy Supply Options
Source: Torcellini, Pless and Deru, 2006

ENERGY BALANCE

PERIODS OF THE BALANCE
The period of time for which the calculations are implemented can vary from the whole life cycle of a building, the that the building is operated or an annual period as is widely used. Moreover, seasonal or monthly balances can be used.

According to Hernandez and Kenny (2010), referring to a balance of the whole life cycle of the building apart from the operating energy use, also the energy embodied of construction, materials and technical installations can be used.

The annual balance period is the most commonly found the ZEB definitions in literature. The monthly balance may be useful in cases where the amount of on-site renewable electricity is equal only to electricity use and not other energy loads of the building. The excess electricity generation is not taken into account in the calculations. Thus a net ZEB with a monthly balance is rarely possible. (Marszal et al., 2012)

TYPES OF BALANCE
There are 2 types of balances that only refer to on-grid connected ZEBs. The first is the balance between the energy use and the renewable energy generation. The second type of balance is the energy delivered to the building vs the energy fed back to the grid. For off-grid ZEBs only the first balance is applicable. (Marszal et al., 2012)

Both balances are primarily the same, with the exception of the use Combined Heat and Power (CHP) generator, that can only refer to the latter balance type. A basic difference is the application time spectrum. The balance between the energy use and the renewable energy generation refers to the design phase of the building. The balance of the energy delivered to the building vs the energy fed back to the grid, is viable for the monitoring phase. (Marszal et al., 2012)

METRICS OF THE BALANCE

PRIMARY OR SOURCE ENERGY
The EPBD definition for a ‘Nearly Zero Energy Building’ refers to the primary energy as the metric for the energy balance. The primary energy considers the energy use of the building (heating, cooling, ventilation, lighting, pumps and fans, other technical service systems, DHW, cooking, appliances, lighting) and the energy-saving by RES generations. (Hamdy, Hasan and Siren, 2013)

The net zero site energy means site energy production of at least the same amount as it uses in a year, independent of the type of energy produced or used. (Hernandez and Kenny, 2010)

In the ‘net-zero energy source’ definition, imported and exported energy are multiplied by a primary energy conversion factor, thus allowing for some flexibility in the use of heating fuels. For example, if electricity is being sold directly to the grid in a location where the electricity primary factor is high, the ‘net-zero energy source’ definition would allow the use of larger quantities of a heating fuel from a source with a smaller primary energy factor. (Hernandez and Kenny, 2010)

SITE ENERGY
Site energy refers to the amount of energy delivered to the building, that does not include transmission, delivery, and production losses is called site energy. Organizations such as DOE are concerned with national energy numbers, and are typically interested in primary or source energy. A building designer may be interested in site energy use for energy code requirements. (Torcellini, Pless and Deru, 2006)
BUILDING-RELATED
According to the international standard EN 15603:2008, the energy calculations for a building should include only the energy use that is independent of the occupant behaviour, actual weather and environmental condition. Thus, for non-residential buildings such as office buildings as they are the subject of research for this Thesis and following energy loads may be taken into account: heating, cooling, ventilation, humidification/dehumidification, hot water and lighting. (Marszal et al., 2012)

USER-RELATED
Many calculation methodologies in the literature take into account the total energy use of the building including both the building and user related energy.

EMBODIED ENERGY
The embodied energy is not widely used for the energy calculations of a building. (Marszal et al., 2012)

ZEB DEFINITION FOR THIS RESEARCH

The basic elements for the energy metering of a building are building systems, energy grid and weighting systems. In order to make a clear balanced calculation for the net zero goal, a boundary needs to be clarified for the building system with on-site renewable. Inside this boundary, the building system consumes delivered energy, such as electricity, natural gas, from the on-site renewable and energy grids, and outputs energy back to the grid when the REP (renewable energy power) system generates excess electricity.

Because of different design goals, different weighting systems are chosen to calculate the net energy obtained by the entire building system. For example, building owners typically care about energy costs, so they prefer to choose a weighting system in the cost balance, rather than the energy balance. Finally, weighted demand and supply are compared to check whether the net zero balance can be achieved based on the specific technology solution. This can be considered as the operating mechanism of basic NZEB evaluation.

The conventional definitions of NZEB are mainly based on the annual energy use of the building operation. Thus, the aim of NZEB commonly represents the annual balance of a grid connected building without consideration of energy accounting in the whole life cycle of a building. An integrated solution which can meet the annual balance for a building may not be able to achieve the net zero goal for every month, or some others smaller time scales.

In most cases, only 2 parameters: consumption of the building and generation of RES (renewable energy source), are considered in the net energy calculation and evaluation. (Deng, Wang and Dai, 2014)

So for this research the following definition for a net Zero Energy Building are considered:

<table>
<thead>
<tr>
<th>Connection to the energy grid:</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-grid</td>
</tr>
<tr>
<td>off-grid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Renewable supply option:</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-site</td>
</tr>
<tr>
<td>off-site</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy balance:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Monthly</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Energy used/ Energy generated</td>
</tr>
<tr>
<td>Energy from grid/ Energy fed into the grid</td>
</tr>
<tr>
<td>Metrics</td>
</tr>
<tr>
<td>Primary energy</td>
</tr>
<tr>
<td>Site energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy end uses:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building related</td>
</tr>
<tr>
<td>User related</td>
</tr>
<tr>
<td>Embodied energy</td>
</tr>
</tbody>
</table>
4.3 HIGH-RISE DEFINITIONS

The following definitions apply to different types of high-rise buildings and also some information on how the height is defined, is given.

SKYSCRAPER

- Britannica Concise Encyclopedia:
  The skyscraper is a very tall high-rise building. The term originally applied to buildings of 10-20 stories, but now generally describes high-rises of more than 40-50 stories. (Raji, 2016):

- Emporis Standards:
  A multistory building at least 100 meters tall. (Raji 2016)

- Ken Yeang:
  The term skyscraper is used (in his book) as an abbreviation for the large high-rise intensive building type, generally regarded as being over 10 stories and which can be a commercial, residential, hotel or mixed use. (Raji 2016)

HIGH-RISE BUILDING

- Emporis Standards:
  A multistory structure between 35-100 meters tall, or a building of unknown height from 12-39 floors. (Raji 2016)

- Massachusetts, United States General Laws:
  A building higher than 70 feet (21m) (Raji, 2016)

TALL BUILDING

HEIGHT RELATIVE TO CONTEXT

It is not just about height, but about the context in which it exists. Thus whereas a 14-story building may not be considered a tall building in a high-rise city such as Chicago or Hong Kong, in a provincial European city or a suburb this may be distinctly taller than the urban norm. (Ctbuh.org, 2017)

PROPORTION

A tall building is not only about height but also about proportion. There are numerous buildings that are not particularly high, but are slender enough to give the appearance of a tall building, especially against low urban backgrounds. Conversely, there are numerous big/large footprint buildings that are quite tall but their size/floor area rules them out as being classed as a tall building. (Ctbuh.org, 2017)

TALL BUILDING TECHNOLOGIES

If a building contains technologies which may be attributed as being a product of “tall” (e.g., specific vertical transport technologies, structural wind bracing as a product of height, etc.), then this building can be classed as a tall building. Although number of floors is a poor indicator of defining a tall building due to the changing floor to floor height between differing buildings and functions (e.g., office versus residential usage), a building of perhaps 14 or more stories – or more than 50m in height – could be used as a threshold for considering it a “tall building.” (Ctbuh.org, 2017)

SUPERTALL AND MEGATALL BUILDING

The CTBUH defines “supertall” as a building over 300m in height, and a “megatall” as a building over 600m in height. As of June 2015 there were 91 supertall and 2 megatall buildings fully completed and occupied globally. (Ctbuh.org, 2017)

WAYS OF MEASURING A TALL BUILDING

HEIGHT TO ARCHITECTURAL TOP

It is the distance measured from the level of the lowest, significant, open-air, pedestrian entrance to the architectural top of the building, including spires. For the height calculation, the measurements of antennae, signage, flagpoles or other functional-technical equipment are not included. This measurement is applied to define the Council on Tall Buildings and Urban Habitat (CTBUH) rankings of the “World’s Tallest Buildings.” (Ctbuh.org, 2017)

HIGHEST OCCUPIED FLOOR

This is measured from the level of the lowest, significant, open-air, pedestrian entrance to the finished floor level of the highest occupied floor in the building. (Ctbuh.org, 2017)

BUILDING VS. TELECOMMUNICATIONS TOWER

A tall “building” can be classed as such (as opposed to a telecommunications/observation tower) and is eligible for the “Tallest” lists if at least 50% of its height is occupied by usable floor area. (Ctbuh.org, 2017)

HIGH-RISE DEFINITION FOR THIS RESEARCH

For this research the high-rise building is considered a multistory structure between 35–100 meters tall. The building optimized was set as a building of 101 meters tall with 31 floors. (Ctbuh.org, 2017)
4.4 COMFORT CONSIDERATIONS IN A Z.E.B.

A primary goal of buildings is to provide shelter, a space to live and engage in activities, and to facilitate provision of a comfortable environment. In the context of net-zero energy buildings, this means they should efficiently provide comfortable conditions while meeting the net-zero energy target. Comfort is tightly linked to energy performance; if occupants are not provided with comfortable conditions, they often adapt in the most convenient and responsive way rather than in energy conserving ways (Cole and Brown, 2009). Therefore, comfort should be critically assessed throughout the design and operation of nZEBs.

According to Taleghani, (2013), there are two different approaches regarding thermal comfort: the steady-state model and the adaptive model. The former, is based on heat exchange processes of the body and is established through information derived from climate chamber tests. Standards that are based on steady state models are among others, ASHRAE55-1992 and ISO 7730. The latter is established through field studies and serve as the base for standards such as the American ASHRAE 55-2010 and the European EN15251. (Taleghani et al., 2013)

THE U.S. STANDARD: ASHRAE 55-2010

The main purpose of the ASHRAE-55 standard is to specify the combinations of indoor thermal environmental parameters (temperature, thermal radiation, humidity, and air speed) and personal parameters (clothing insulation and metabolic rate) that will produce thermal environmental conditions acceptable to a majority of occupants.

THE E.U. STANDARD: EN15251

This standard specifies how to establish environmental input parameters for non-industrial buildings like single family houses, apartment buildings, offices for design and energy performance calculations. The guidelines of thermal comfort from this standard are based on the Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission. (Taleghani et al., 2013)
VISUAL COMFORT

The lighting conditions in the interior environment form one of the system factors that influence the productivity and satisfaction of the individual. The ability to move and adjust one’s work position according to light is important in the workplace (Baker and Steemers, 2002). Visual tasks need to be performed with accuracy, safety and at reasonable speed. These requirements imply various constraints on illuminance levels and luminance contrasts, mainly in the central part of the visual field. The visual field should not provoke excessive eye-strain or result in glare sensation. Moreover, the field of view should present both aesthetic qualities and a certain degree of interest. It is commonly recognized that access to daylight is very much appreciated by occupants. (Baker and Steemers, 2002)

Façades with more than a 60% window-to-wall ratio should be avoided, as they tend to cause thermal and visual discomfort due to excess daylight and solar gains. (Athienitis and O’Brien, 2015) Fixed shading devices function better for equator facing façades and do not perform well for non-equator-facing façades. The glazing construction typically has lower thermal resistance than opaque wall or roof constructions and can cause unwanted solar gains, especially in cooling-dominated climates and for buildings that have high internal gains. (Athienitis and O’Brien, 2015) In addition, it has been shown that occupants prefer shallow (no more than 15 or 20m wall to wall) over deep buildings, due to daylight availability, views to the outdoors, and natural ventilation potential (Leaman and Bordass, 2007).

ACOUSTIC COMFORT

Acoustic comfort describes the indoor acoustic conditions of a building with regard to providing a healthy and productive environment for occupants.

Natural ventilation provides fresh air to supplement or temporarily eliminate the need for mechanical ventilation. However, open windows often introduce outdoor noise into the workplace, especially in urban areas or beside busy streets. Furthermore, cross-ventilation requires an open concept design. However, a lack of partitions between spaces results in higher levels of sound transmission. Thus, distracting conversations and other noises can cause poor occupant concentration and comprehension. Deep daylight penetration in a space also requires an open concept design, similarly to natural ventilation. Exposed thermal mass (e.g., concrete structures) facilitates greater ability to absorb solar gains, which is an important element of low-energy passive buildings. However, hard smooth surfaces are also poor sound absorbers and can lead to poor acoustic comfort if such surfaces dominate a space. (Athienitis and O’Brien, 2015)

The strategies to reduce poor acoustic quality include absorbing, blocking, and covering noise. Absorbing means the use of strategically placed surfaces to reduce sound reflectance in a space. Blocking requires that the source of sound be isolated. Covering means masking sounds with white noise generators such that individual sounds are indistinguishable. (Athienitis and O’Brien, 2015)

INDOOR AIR QUALITY

Indoor air quality is a measure of the healthiness and comfort of air in buildings. Contaminants in the air are normally categorized as gaseous, particulates, or microbial. The main contaminants of concern include: tobacco smoke, radon, molds, legionella, carbon monoxide, bioeffluents, volatile organic compounds (VOCs), asbestos-fibers, ozone, and carbon dioxide. Their origin can be materials and substances that are indoors, occupants, equipment and HVAC distribution, or the outdoors.

The first approach, to attempt to eliminate the source of contaminants, is the preferred option because it requires no maintenance or operating energy use. Use of low-VOC paints, furniture, and other finishes are also good approaches to achieve this. Careful design of walls and HVAC systems to minimize chronic moisture or sitting water is essential to minimize mold growth and other bioaerosols. The second approach is ventilation improvements. Electrical energy is used for fans and pumps and thermal energy for conditioning supply air. The thermal energy demands of ventilation can be partly reduced using heat or energy recovery ventilation.

CONCLUSIONS

For this research, an adaptive thermal comfort model is going to be used, since the building that will be optimized, it will be a building with hybrid ventilation mode, both mechanically and naturally ventilated. The climatic conditions of Athens, offer temperature within the thermal comfort range for a large part of the year and the choice for a mixed mode ventilated system would be a more logical choice for this research.
The following high-rises were chosen for this precedent analysis, because they are located in climates similar to that of Athens and are also office buildings, with the exception of one high-rise that is a residential building.

<table>
<thead>
<tr>
<th>Location</th>
<th>Use</th>
<th>Climate</th>
<th>Storeys</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torre Agbar</td>
<td>Office</td>
<td>Humid subtropical</td>
<td>38</td>
<td>2005</td>
</tr>
<tr>
<td>Bosco Verticale</td>
<td>Residential</td>
<td>Humid subtropical</td>
<td>18-27</td>
<td>2011</td>
</tr>
<tr>
<td>1 Bligh Street</td>
<td>Office</td>
<td>Subtropical</td>
<td>30</td>
<td>2011</td>
</tr>
<tr>
<td>Commerzbank</td>
<td>Office</td>
<td>Temperate</td>
<td>56</td>
<td>1997</td>
</tr>
<tr>
<td>Post Tower</td>
<td>Office</td>
<td>Temperate</td>
<td>42</td>
<td>2002</td>
</tr>
</tbody>
</table>


5.1. TORRE AGBAR

Barcelona and its metropolitan area has a humid subtropical climate (Köppen-Geiger climate classification: Cfa), bordering a Mediterranean climate (Csa) with mild winters and hot summers. Its average annual temperature is 21.2°C during the day and 15.1°C at night. In the coldest month (January), typically the temperature ranges from 12 to 18°C during the day and 6 to 12°C at night. In the warmest month (August), the temperature typically ranges from 28 to 32°C during the day and about from 22 to 24°C at night. Large fluctuations in temperature are very rare. December, January and February are the coldest months. The summer season lasts about six months, from May to October. July and August are the warmest months (Worldweatheronline.com, 2017).

Sunshine has a duration of 2,524 hours annually. It has an average of 4.5 hours of sunshine per day in December and an average of 10 hours of sunshine per day in July. (Worldweatheronline.com, 2017)
BUILDING SITE

The Torre Agbar has a total surface area of 50,693 m², out of which 30,000 m² is occupied by offices, 9132 m² by parking, 3210 m² of technical facilities and 8132 m² by services including an auditorium. The building has been designed by the architects Jean Nouvel and Fermin Vazquez. It was officially opened on September 16, 2005. The building is located in Barcelona, next to Plaça de les Glòries.

BUILDING GEOMETRY

The 38-story tower has 2 non-concentric oval cylinders crowned by a glass and steel dome and reaches a height of 142m. It has 34 floors above ground – 28 floors for office use, 3 technical floors for centralized installations, one floor for the cafeteria, one for multipurpose rooms and one for a bird’s-eye view in the tower’s dome. The building has 4 floors below ground level – 2 floors for a 316-seat auditorium and 2 for parking. There are 11 elevators in total, including 1 service elevator and 2 for the underground floors. Stairs, service lifts and the building service installations are located in the core of the skyscraper. (Nastace, 2015)

BUILDING ENVELOPE

The envelope has a U-value of 0.7 W/m²/K. (Institute for Energy and Transport, European Commission, 2011)

Torre Agbar has 4,500 windows to maximize natural ventilation and reduce energy costs by optimizing sunlight usage. At night, it uses 4,500 RGB LED luminous devices that are computer-controlled and help generate luminous images in the façade. This building’s double skin façade consists of an inner concrete façade. Upon it, boards are mounted with integrated windows in the wall’s structure. The exterior façade is made of laminated glass modules, anchored by a steel structure on the interior concrete façade. There are 56,619 transparent and translucent glass plates. The louvres are tilted at different angles calculated to deflect the direct sunlight. (Nastace, 2015)

Energy consumption for air conditioning is reduced by using external temperature sensors, which control the opening and closing tabs on the outer façade, adjusting the flow of fresh air in the cavity, allowing for natural ventilation. The regulation of air flow and natural ventilation is increased through double glazing in the dome. Changing the angle of the mobile scales insulates the building from the cold of winter and the heat of summer.

BUILDING SERVICES

Elevator routes are optimized with the aid automated systems to prevent unnecessary consumption. Energy-efficient technologies were used also in the case of the building services. For the air conditioning and heating of the building, a VRV system was installed with 27 different climate zones per floor. A central system regulates and optimizes the air-conditioning and heating needs depending on the outdoor temperatures and the occupation of the offices. The building has an annual primary energy demand of 402.70 kWh/m². (Institute for Energy and Transport, European Commission, 2011)

RENEWABLE ENERGY

Some of the glass louvres on the south side have photovoltaic surfaces to generate electricity. Also phreatic water is used for secondary applications (cleaning paving and ornamentation) in order to save water.
5.2. BOSCO VERTICALE

CLIMATE

Milan has a humid, subtropical climate that is characterized by hot and humid summers with cold and damp winters. It experiences four seasons and a wide range of temperatures, typically varying from -1°C to 31°C. There is often snowfall from December through February (an average 300 to 400 mm). The remainder of the year consists of rain in springtime and temperatures ranging from 20°C to 30°C during the summer and -1°C to 10°C during the winter. The most common forms of precipitation are light or moderate rain, occasionally followed by thunderstorms. (Giacomello and Valagussa, 2015)
BUILDING SITE

The Bosco Verticale project consists of 2 residential towers located in Porta Nuova district in Milan. The Porta Nuova area is comprised of 34 hectares. The area was meant to be turned into an office district, according to the city plan of 1953, with the objective of decongesting the city center by relieving growing traffic. In 2004 according to a revised urban plan the new Porta Nuova is divided into three neighborhoods. It takes advantage of the proximity to the city center and of transportation accessibility. The project is near 2 railway stations, 2 underground metro lines and a third under construction. It introduces a diversity of uses to the area, including offices, retail and residential buildings, interconnected by a large park with pedestrian paths. (Giacomello and Valagussa, 2015)

The architects consider this project as a good example of increased density and anti-urban-sprawl measures for the cities of the future, which will be more densely built than they are today. (Giacomello and Valagussa, 2015)

BUILDING GEOMETRY

The facade of the two towers are oriented precisely in the four cardinal directions. The two towers have the ability to host 480 big and medium size trees, 250 small size trees, 11,000 groundcover plants and 5,000 shrubs (the equivalent of a hectare of forest). On the one hand, the green façade provides protection from the sun in the summertime and improves the microclimate for a better living atmosphere. The two towers are of different heights, but are characterized by the presence of vegetation distributed throughout deep cantilevered terraces, on all orientations and along all facades of both towers. Tower D is 85 meters high and consists of 18 floors, while Tower E is 177 meters high and consists of 27 floors. The floor plan of the two towers are different: the floor plates of Tower D have a surface area approximately 500 m², while the floor plates of Tower E have a larger surface area of 660 m². (Giacomello and Valagussa, 2015)

BUILDING ENVELOPE

The envelope is highly vegetated. In plan, the vegetation is located about 2.3m to 3.1m from the external wall. The envelope of the project is a combination of external walls, cantilevered terraces and vegetation. The balconies extend 3.35 meters from the apartments on all four sides of the building. The characteristics of all 40 of the tree types used here were precisely analyzed and even tested in a wind tunnel in order to determine the most suitable species for the requirements of height, wind strength and sunlight at every level of the building. The olive and pomegranate trees were anchored in the substrate layer of the concrete floor plates of Tower D have a surface area approximately 500 m², while the floor plates of Tower E have a larger surface area of 660 m². (Giacomello and Valagussa, 2015)

EXTERNAL WALLS

The infill wall is made of honeycomb bricks. Both these infill walls and the structural reinforced concrete are coated with panels of mineral thermo-acoustic insulation. The exterior finish consists of stone cladding, ventilated and supported by metal frame anchored to the infill wall of honeycomb bricks. All the external walls, regardless of orientation, have the same composition. Terrace doors and windows of each apartment extend from floor to ceiling. This helps to extend the illuminated surface area of the exterior walls to the interior and emphasizes the protective shading role of the trees. (Giacomello and Valagussa, 2015)

THE CANTILEVERED TERRACES AND PLANTERS

The floors of the terraces are covered on the top by a thin layer of thermal insulation, a waterproofing membrane and a lightweight concrete layer with stone cladding. A thin layer of thermal insulation and a double layer of white plasterboard are applied on the underside. The next layer consists of a single layer of separation and drainage. (Giacomello and Valagussa, 2015)

THE VEGETATION

The vegetation is the outermost exterior element of the envelope and represents a filter between the interiors of the towers and the urban environment. The plants act as a sunscreen, both deciduous and evergreen trees are used. The shielding capacity of the leaves reduces the absorption of solar radiation of the shaded layers, and therefore the heat transfer to the indoors. The plants also act as a windscreen. (Giacomello and Valagussa, 2015)

BUILDING SERVICES

The floor is provided with mechanical ventilation, at a rate equal to 0.3 air changes per hour. For the energy analysis of the building, the HVAC system is simulated with EnergyPlus with a simplified heating/cooling machine named in the software “Ideal Loads Air System”. The set-points for heating are 20 °C and for cooling 24 °C. The space heating energy needs are 23.2 kWh/(m²/year) and for cooling 7 kWh/(m²/year). The electricity consumption for space heating is 10.7 kWh/(m²/year) and for cooling is 2.0 kWh/(m²/year). (Giacomello and Valagussa, 2015) In the calculations, the Coefficient of Performance (COP) of heat pumps is 2.5 and the Seasonal Energy Efficiency Rating (SEER) of the chiller is 3.5. The main thermal benefits derived by the presence of the cantilevered terraces and plants around the external walls occur in summer and terraces clearly affect cooling loads more significantly than trees. (Giacomello and Valagussa, 2015)

In the final analysis, the calculation of the yearly energy-consumption for space heating and cooling highlights that the presence of terraces and vegetation decreases the yearly electricity consumption by about 75% (12.7 kWh/(m²/year)) with respect to a building with no terraces and vegetation. (Giacomello and Valagussa, 2015)

RENEWABLE ENERGY

Plant irrigation is mostly taken care of through the use of gray water. The project takes advantage of a large aquifer under the city for heating and cooling. Using ground source heat pumps to access the aquifer, the building services are balancing the cooling and heating demands to minimize energy use at Bosco Verticale. The mechanical systems providing heating and cooling have the ability to simultaneously provide heating and cooling so, for example, hot water for underfloor heating can be provided to heat north-facing rooms, at the same time as apartments in south-facing rooms are cooled via ducted fan coil units. The radiant floor is also cooled through a heat exchanger connected to the aquifer loop, which helps lower the overall cooling load. Air handling units are positioned at the top and bottom of the larger tower to balance air flows. The heat pumps work more efficiently during the spring and autumn, when different rooms in the tower need to be cooled and heated simultaneously. When the unit provides cooling for overheated rooms, the heat rejected from the condenser can be used to bring room temperatures in other parts of the towers up to the desired set-point. (Giacomello and Valagussa, 2015)
CLIMATE

Sydney has a temperate climate with warm summers and mild winters, moderated by proximity to the ocean. The summer months of December, January and February are known for high temperatures averaging around 26 °C. However, cloud-free skies and extremely sunny days can create summer temperatures which approach 40 °C. Rainfall is evenly spread throughout the year, August and September being the driest months. Winter weather remains warm with an average temperature of 17 °C. (Worldweatheronline.com, 2017)
BUILDING SITE

The 1 Bligh Street building has a compact elliptical form with 12% less surface area than a rectilinear building of the same volume, thus reducing the heat gain/loss through the building envelope. In addition, a naturally ventilated double-skin façade with 60 cm cavity helps to reduce the heat gain through the envelope. The building’s orientation and configuration of plan are mainly derived from the urban grid and the desire to maximize the view, not from environmental concerns. While the service core could have been used as solar buffer on the hot east and west side, it is placed on the south side. (Raji et al., 2016)

BUILDING GEOMETRY

The compact elliptical form increases the ratio of the building’s volume-to-surface area, therefore reducing heat gain and loss through the envelope and optimizing energy performance. The form also minimizes wind turbulence and downdrafts, improving the environment at street level. (Raji et al., 2016)

In contrast to an office building with a central circulation core that requires artificial lighting and conditioning, the 120m tall atrium is exploited as a day-lit and naturally ventilated circulation space, minimizing electricity demands and HVAC energy consumption. (Raji et al., 2016) Fresh air flows into the atrium through the sky garden at mid-height and operable glass louvers in the facade of the ground floor lobby. Stack effect exhausts the atrium through openings in the glass roof of the atrium. The atrium naturally ventilates balconies and corridors which surround it on each floor. (Wood and Salib, 2013)

BUILDING ENVELOPE

For exploitation of daylight, lighting 1 Bligh Street has a fully transparent façade. However, just 30% of permanent working stations are within 5 meters of this façade. Due to this deep plan (23.5 m from façade to central void), there are 3 working zones between the building perimeter and the atrium. A central atrium and transparent partitions are used to increase natural light penetration. Temporarily used spaces such as meeting rooms are placed in the mid-zone. (Wood and Salib, 2013)

The building’s exterior has a double-skin façade consisting of a double-glazed insulating layer with a very high-performance low-E coating and a single-glazed laminated low-iron glass. The 600mm cavity of the facade is horizontally continuous along the length of the facade, but vertically segmented at each slab level. The outer glass panels have fixed louvers at the edge of each floor slab, allowing fresh air to enter at the bottom of each cavity and exhaust at the top. Airflow within the facade cavity helps maintain a constant average temperature in the building, reducing the use of HVAC systems (Raji et al., 2016). However, the double-skin facade is not used to naturally ventilate the building, thus the inner facade is not operable and is solely used to protect the blinds.

The 1 Bligh Street has two strategies for ventilation. The atrium is naturally ventilated but the working areas are fully mechanically ventilated. The building is designed in a way that the perimeter cellular offices may potentially use single-sided natural ventilation if the interior glass panels are replaced with operable ones. Nevertheless, the deep floor plate does not allow for cross ventilation. (Raji et al., 2016) The inability of the occupants to control the operation of the ventilation system (only BMS) may lead to limited comfort.

BUILDING SERVICES

1 Bligh Street uses 73.7 kWh/m² of gas to feed a tri-generation system which generates electricity, heating and cooling. (Raji et al., 2016)

Curved solar thermal collectors provide hot water to drive the absorption chiller and generate cooling. This system is up to 50% more efficient compared to conventional grid-connected systems. (Raji et al., 2016)

The building uses mechanical cooling and natural ventilation operating in different areas of the building, mostly independently. The lobby, atrium, balconies and corridors are naturally ventilated throughout the year. The office spaces are conditioned in two zones, using highly efficient chilled beams at the perimeter and a variable-air-volume (VAV) system in the interior. The lobby floor has in-slab heating that uses waste heat from the HVAC system. (Raji et al., 2016)

The building management system (BMS) controls the natural ventilation in the atrium. The BMS also controls the blinds in the cavity of the double-skin facade using sun-tracking and photo-sensors. (Raji et al., 2016)

The energy savings for the heating and cooling of the building are estimated to be approximately 63% over a typical Australian office building. According to estimations, the natural ventilation could be potentially suitable for approximately 35-40% of the year in the office spaces. (Raji et al., 2016)

RENEWABLE ENERGY

An area of 500 m² of roof-mounted solar panels in combination with the large tri-generation unit, provide cooling.

The materials used in the construction of the tower also contribute to the sustainability of the building. Over 20% of the aggregate used in concrete was recycled material, and about 41% of the cement was replaced with industrial waste by-products. 90% of the structural steel has a recycled content of at least 50%. Lastly, all timber used was either recycled or from an FSC-certified source. (Wood and Salib, 2013)

Blackwater treatment facility filters sewer water from the municipal waste stream to flush toilets and provide water for the cooling towers. This system provides 100,000 liters per day, reducing the demand on municipal potable water by 90%. Recycled water is also used to irrigate a 9.7m high green wall. Recycled rain water is also used to irrigate decorative plantings spread throughout the building. (Wood and Salib, 2013)
5.4. COMMERZBANK

CLIMATE

Frankfurt is located in a warm temperate climate with mild weather all year-round. Summers are typically warm and sunny with light rain. Highest temperatures can be from 24 °C to 30 °C during the day and dropping to 15°C in the evenings. During the winter, especially in the coldest month, January, daytime temperatures hover around 4°C and at night drop just below freezing.

Figure 5.14: mean monthly temperatures for Frankfurt
Source: http://www.worldweatheronline.com/

Figure 5.15: solar radiation for Frankfurt
Source: Climate Consultant 6.0

Figure 5.16: wind speed for Frankfurt
Source: Climate Consultant 6.0
BUILDING SITE

The tower is centrally located within the densely built financial district of Frankfurt am Main. It has a 6 story high base which includes a plaza, a bank, auditorium, garage, shops and residences.

BUILDING GEOMETRY

The building has a triangular plan with a central atrium running the full height of the building but divided into four segments, around which sky gardens and office spaces are arranged in a spiraling configuration. The three corners of the triangle are the main structural elements and include vertical circulation and services.

BUILDING ENVELOPE

The building is divided into 12-story “villages” stacked on top of each other, with a central atrium segmented through the use of steel and glass diaphragms at the boundary level of each segment. The diaphragms limit stack pressures and smoke spread in the central atrium, isolating each segment to be ventilated completely independently from the others. Each segment has a 4-story sky garden positioned on each of the three faces of the building, configured in a spiraling pattern up the building, thus allowing ventilation to occur regardless of wind direction as there is always a windward garden to admit the air to the central atrium and a leeward garden to exhaust it. The atrium and sky gardens can be considered as sheltered, quasi-external buffer spaces between external and internal environments. (Wood and Salib, 2013)

The offices are located at the 16.5 meter wide wings. The wings are split by a wide central corridor with half the offices facing the central atrium and the other half facing the exterior. The external-facing offices are ventilated directly from the external envelope through a double-skin facade system. The cavity is ventilated at the top and bottom through 125mm continuous void. Small aerofoil-section strips are positioned at sill levels just above/below these ventilation slots to improve airflow through the cavity and avoid short circuiting of air. The office spaces on the inward side facing the atrium, are ventilated via windows facing the atrium from air moving through the sky gardens. The ventilation strategies for the inward-facing offices, outward-facing offices and central corridors work independently of each other. (Wood and Salib, 2013)

BUILDING SERVICES

Comfort was a critical factor at the design stage, therefore the building was designed with a Complementa-ry-Changeover system which switches between mechanical and natural ventilation on a seasonal or daily basis. (Wood and Salib, 2013)

The building was designed to be naturally ventilated for approximately 60% of the a yearly period.

Direct sunlight is blocked through the use of motorized blinds integrated in the double-skin facade. Additionally, light sensors limit the use of artificial light.

Mechanical ventilation introduces conditioned air into the offices via supply ducts above the office ceiling panels. On hot days a water-filled cooling system integrated in the ceiling panels is used. In winter, supplemental heating is provided through panel radiators located beneath perimeter windows in office area and under-floor heating in the sky gardens. Sky gardens always remain naturally ventilated. The central corridor zones between office spaces in the office wings are mechanically ventilated at all times through an air supply and exhaust system. (Wood and Salib, 2013)

The central BMS controls the operation of motorized windows, blinds, chilled ceilings, air-conditioning and perimter to achieve an optimum balance between occupant comfort and energy efficiency. The BMS thus controls the internal climate system according to the number of people, the usage of the system, set-point temperatures (26°C in summer-17°C in winter), wind, solar intensity and humidity measurements from the weather sensors. Occupants have control over their environment for systems such as lighting, blinds and opening windows. (Wood and Salib, 2013)

The total annual thermal energy consumption ranges between 105 and 128 kWh/m². While natural ventilation is attainable for 80% of the year and some zones are naturally ventilated during the entire period. (Wood and Salib, 2013)

Besides the successful energy-saving design, the amount of potential, leasable floor area occupied by the atria and sky-gardens is considerable and may not be viable on a more commercial office building.

RENEWABLE ENERGY

As a measure of recycling water, gray water from the cooling towers is used to flush toilets.
5.5. POST TOWER

CLIMATE

The climate and temperature of Bonn are often influenced by the nearby Rhine Valley and strong westerly maritime winds which blow in from the North Sea. In general, the weather is characterized by four distinct seasons and cloudy skies. Winter temperature average is around 3°C climbing to 10°C in spring. Summer temperatures top 20°C to 25°C. Rainy weather occurs unexpectedly. (Worldweatheronline.com, 2017)

Figure 5.18: mean monthly temperatures for Bonn
Source: Worldweatheronline.com, 2017

Figure 5.19: solar radiation for Bonn
Source: climate consultant 6.0, 2017

Figure 5.20: wind speed for Bonn
Source: climate consultant 6.0, 2017
BUILDING GEOMETRY

The tower’s form consists of 2 offset elliptical segments separated by a 7.2 meter wide atrium that faces west toward the City of Bonn and east towards the Rhine River. This full-building-height atrium is segmented into four parts, the top one is 11 stories high and the rest 9 nine stories high. Cellular offices are located in the perimeter, with conference rooms and core functions located toward the center of the building. The two parts of the tower are connected at every level with steel and glass bridges. The two main facades of the office segments face north and south, respectively, while the facades of the sky gardens have east and west orientations. (Wood and Salib, 2013)

BUILDING ENVELOPE

The building includes a transparent floor-to-ceiling glazing in all office space. The natural ventilation strategy of the building relies on both cross and stack ventilation and is based on a double-skin facade system which supplies air to the offices and a central atrium sky garden which exhausts it. The double-skin facade varies in both width and detail on the north and south facades, but all consist of an outer single-glazed skin, full-floor operable sunshades in the cavity and an inner skin of floor-to-ceiling insulated double-glazing. The double-skin facade extends both vertically and horizontally along the north and south facades, with a single-skin facade enclosing the sky gardens between. (Wood and Salib, 2013)

The outer skin acts as a protective layer mitigating high wind speeds. By shielding the wind, it achieves wind pressures/airflow rates similar to a low-rise office building. Inside the double-skin facade cavity, operable flaps at the lower floors draw in cooler air while the upper floors exhaust hot air. In the summer the operable flaps are opened to maximum angle and during winter they are closed and the facade cavity acts as a thermal buffer. After normal working hours the windows can be centrally opened to provide night flushing with cool air. (Wood and Salib, 2013)

The underside of the concrete slabs are left exposed in the office space so that their high thermal capacity can be used to absorb and store a large amount of heat energy during the day. Night cooling cools the exposed slabs after working hours.

BUILDING SERVICES

The Post Tower is designed as a Zoned/Complementary-Changeover building. Interior conference and meeting room space are conditioned mechanically and the exterior cellular offices use either natural or mechanical ventilation. During summer or winter extremes the conditioning is augmented by perimeter fan coil units and radiant ceilings. The fan coils draw in outside air from the double-skin facade and then heat or cool the air. Additional conditioning is provided through radiant, exposed concrete soffits with embedded piping that circulates cool water (18°C) and warm water (28°C). The sky gardens rely fully on natural ventilation. (Wood and Salib, 2013)

The primary energy predominantly used for ventilation and thermal conditioning is electricity, that drives the water pumps. During the cooling season, the fan coil units and the radiant slab system utilize a ground water exchange with cool water from the Rhine River. For heating, the energy source is district heating provided by the city. (Wood and Salib, 2013)

A building management system (BMS) uses local sensors controlling the operation of the outer facade flaps and motorized operable windows of the inner facade to adjust natural ventilation. The BMS setpoints have a range of 22°C and 26°C in the office spaces and 18°C and 28°C in the sky gardens. The BMS also controls the radiant concrete slabs, the sunshades located in the double-skinned cavity, the dimming of the artificial lighting and the vents located in the exterior facade of the sky garden. Office occupants can override the BMS to ensure their individual comfort. (Wood and Salib, 2013)

The building was designed to utilize 65 kWh/m² for ventilation, heating and lighting.

A decentralized fan coil unit coinciding with the radiant cooling system replace a traditional centralized, ventilation based air-conditioning system. This results in significant energy, cost and space savings. (Wood and Salib, 2013)

CONCLUSIONS

Through the review of these high-rise buildings it can be concluded that natural ventilation and shading are the two most commonly used strategies in order to achieve lower energy consumption. Atria, double-skin facades and in some cases sky-gardens are commonly used as strategies aiding the natural ventilation strategy. Moreover mixed-mode ventilation with the parallel use of building management systems (BMS) are widely applied with the aim to ensure the required indoor thermal comfort levels. Finally, solar collectors are mainly used in countries with higher annual solar radiation levels like Spain and Australia. In most case studies the pv panels are used for the production of electricity, since office buildings have higher electricity demands compared to hot water demands.
6.1 ZEB STRATEGIES REVIEW

TRIAS ENERGETICA

A concept relative to environmental design is the “Trias Energetica”. Originally, it was introduced by Kees Duyvesteijn in 1989 and was called the Three Stage Approach. That approach included not only energy but also materials and water. (Duyvesteijn 1989) In 1996 Lysen presented this same approach but then only for energy. That approach was called the Trias Energica. (Lysen, 1996) Trias Energetica is a stepped strategy. Most favourable measures were part of the first step, that aims to prevent the use of energy. The 2nd step refers to using renewable energy sources as widely as possible. The last step refers to the remaining energy demand that is not covered by the previous 2 steps. This step entails using fossil fuels as efficiently as possible. (Konstantinou, 2014)

The Trias Energetica strategy, proposes passive and active measures. The passive measures entail exploiting the design and construction properties of the building envelope, in order to reduce energy demand. The 2nd and 3rd step entail HVAC systems and solar active systems from producing energy. (Konstantinou, 2014)

The steps of the Trias Energetica methodology are the following:
1. Energy demand reduction
2. Renewable energy employment
3. Clean and efficient use of fossil fuels

NEW STEPPED STRATEGY

Energy demand reduction is the 1st step in Trias Energetica and usage of fossil fuels in the 3rd step. The New Stepped Strategy is different because it eliminates the use of fossil fuels altogether and the exploitation of waste flows as a new step. (Looman, 2017)

The steps of the New Stepped Strategy methodology are the following:
1. Energy demand reduction
2. Reuse and recycle waste flows
3. Renewable energy employment

The first step of energy demand reduction could mean using passive strategies such as shading or improved insulation of the building envelope.

The second step of reusing and recycling waste flows refers to for example using reused materials such as wood from previously built constructions and also use the construction materials for recycling after the demolition of the building. Other examples would be gray water recycling or connecting building’s with different functions and thus exploiting waste heat or waste cooling.

The third step refers to producing energy from active systems such as photovoltaic panels or solar collectors.
CLIMATE RESPONSIVE DESIGN

According to Looman (2017), climate-responsive design exploits the natural energy sources present in the built environment such as the sun, earth, wind, sky, water, complemented with energy recovery from waste flows for passive or low-energy comfort provision. The building stands between the controlled indoor environment and the dynamic outdoor conditions. Since the outdoor conditions will not always facilitate the indoor comfort demands, the building needs to compensate with certain strategies such as energy conservation, distribution, buffering, recovery and storage. A combination of techniques will result into a comfortable building with an effective energy balance required for heating, cooling, daylight provision, ventilation, hot water and electricity.

Climate Responsive Architecture

<table>
<thead>
<tr>
<th>Energy Need</th>
<th>Natural Source</th>
<th>Energy Treatment</th>
<th>Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Sun</td>
<td>Prevention</td>
<td>Shading</td>
</tr>
<tr>
<td>Heating</td>
<td>Sky</td>
<td>Conservation</td>
<td>Insulation</td>
</tr>
<tr>
<td>Lighting</td>
<td>Sun</td>
<td>Promotion</td>
<td>Daylight</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Wind</td>
<td>Promotion</td>
<td>Natural ventilation</td>
</tr>
<tr>
<td>Electricity</td>
<td>Sun</td>
<td>Promotion</td>
<td>Photovoltaic</td>
</tr>
</tbody>
</table>

Figure 6.1: elements of climate responsive architecture
Source: Looman, 2017

For this research, heating, cooling, electricity and ventilation need will be entailed in the calculations. Looman (2017) refers to strategies that can be used, according to a climate-responsive design, that can lead to reduced energy loads. The different energy aspects to be taken into account in this Thesis are explained below:

HEATING
Due to the wide temperature spectrum between summer and winter conditions in Athens, both cooling and heating energy aspects should be taken into consideration for the design of a building. In order to diminish heating loads, conservation and heat recovery measures should be taken.

COOLING
In the hot and dry climate of Athens, cooling is usually the most representative energy aspect in a building, without excluding heating needs. The design strategies should help the building prevent from overheating. In order to minimize cooling needs the building design should aim to reduce solar heat gains.

VENTILATION
Ventilation is needed for the development of a healthy and comfortable indoor environment. Natural ventilation provides fresh air to the building and when this meets the indoor thermal comfort standards, then this could lead to reduced HVAC loads. Otherwise, mechanical systems should compensate for meeting the required thermal comfort.

6.2 ZEB STRATEGY FOR THIS RESEARCH

In review of the existing stepped strategies that lead to a more sustainable building, with regard to the ZEB definition given by the European Union and referring to the boundary conditions of this research, the following aspect will be addressed in this research, in order to achieve a high-rise office building of reduced energy demands:

1. Reduction of energy demand through:
   - Passive measures
   - Energy efficiency systems

2. Production of on-site renewable energy

The step of reusing the recycling waste flows is out of the boundaries of this Thesis, since the goal is to reduce energy demands of the building and increase thermal comfort.

What is different in the methodology used in this research is the integrated procedure in contrast to the stepped strategies aforementioned (Trias Energetica and New Stepped Strategy) that calculate passive and active systems in separate steps. The methodology used in this research aims to show that by calculating both passive and active systems in an integrated procedure, will lead to better results than the existing stepped strategies. The reason behind this is that some passive and active measures may have conflicting effects upon different energy loads. For example, bigger windows allow for better exploitation of daylight and thus reduced electric loads, but small window allow for more pv panels to be installed in the facade of the building. Leading to increased electricity production.

For this thesis, the optimization process will be comprised of 2 separate steps. The first step refers to the optimization of the building geometry regarding the floor plan layout and the orientation of the building. After this step, an optimal design is chosen as an input for the 2nd final step.

The 2nd step refers to an integrated optimization of building envelope characteristics, the amount of energy generation on the building envelope and the optimization of characteristics of mechanical ventilation systems. By integrating the optimization of envelope, HVAC and energy production, this study aims to show that this integrated approach leads to better results than optimizing each variable/aspect separately. Since many variables can have conflict effect on the final energy loads, such as the window to wall ratio with the pv facade area, the integrated approach will help define the balancing point between passive and active measures. Moreover, the integrated approach will reveal the amount of influence of different design and construction variables on the energy use and thermal comfort of the building.

The simulations in the first step will be implemented with the DesignBuilder software. The simulations of the second step will be implemented by Grasshopper via the Honeybee and Ladybug plug ins, with Energy Plus used for the energy calculations. Grasshopper is used because a connection to the optimization platform of mode-FRON...
TIER is viable within the boundaries of this Thesis. DesignBuilder will be used as a commercial software that allows for a comparison of the results derived from Grasshopper that has more restricted capabilities.

The following chapter elaborates on the characteristics of the building geometry, the building envelope, photovoltaic systems and HVAC systems that will be addressed in this research.

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**INTEGRATED OPTIMIZATION STRATEGY**

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**6.3. BUILDING SITE**

Aiming for a nearly zero energy building, the design must take into account the building site’s specific climate. The local climate can indicate the most suitable passive and active design strategies. Climate also influences aspects of a building design such as the required indoor temperature and the predicted energy loads. All the climatic data needed for this research are included in the EnergyPlus weather files (EPW) used in both DesignBuilder and Grasshopper software. The climatic data of this research are elaborated in chapter 2.2.

Climate data analysis usually involves presenting the annual patterns of the main climatic factors in different forms, such as graphical monthly patterns of the local temperatures, humidity, wind speed, sky coverage, etc. (Givoni, 1992) Those climatic data may be useful for a designer so as to have a sense of what values of energy loads and comfort levels might be expected before the optimization starts.

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**PSYCHROMETRIC CHART**

A psychrometric chart illustrates information about the wet bulb temperature, the dry bulb temperature and humidity (relative and absolute). A psychrometric chart is used to determine the thermal comfort zone using local climatic data.

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Figure 6.3: examples of psychrometric charts
Source: Sustainabilityworkshop.autodesk.com, 2017
These diagrams show the frequency and speed of wind blowing from each direction over a specific period and generally illustrate wind patterns at a site. (Sustainabilityworkshop.autodesk.com, 2017) Wind rose diagrams are helpful for the stage of decision making for the design of a building, but it does not take into account unique micro-climates and site differentiations.

Solar radiation is an important aspect of generating energy from renewable sources in a building. For active strategies, it can be transformed into heat or electricity if it is captured by solar collectors. It also helps in early design stages with regard to mass, orientation and program of the building. The intensity of the sun varies by the clarity of the atmosphere and the angle at which the sun strikes a surface, called the “incident angle”. Incident solar radiation is the amount of solar radiation energy received on a given surface during a given time. Incident solar radiation values are based on two primary components: direct radiation (from the sun) and diffuse radiation (scattered by the clouds and atmosphere). (Sustainabilityworkshop.autodesk.com, 2017)

Stereographic sun path diagrams are used to read the solar azimuth and altitude throughout the day and year for a given position on the earth. Thus, the designer can know the sun’s incidence angles over different orientations in the building site. (Sustainabilityworkshop.autodesk.com, 2017)

The building’s layout and orientation are the 2 aspects that will be optimized in the 1st optimization step.

Plan form and building shape (or compactness) can influence the amount of heat gain/loss through the envelope. Circular and elliptical forms have respectively 25% and 12% less exposed surface area than a rectilinear building of the same volume. Additionally, an aerodynamically shaped building minimizes wind turbulence and downdraft at street level. (Raji, Tenpierik and van den Dobbelsteen, 2016)

According to Givoni, (1994), the appropriate layout for hotter climates is a spread-out building, that allows better natural cross-ventilation than a compact one. In a naturally ventilated building, without active cooling, the indoor temperatures depends on the outdoor temperatures plus the amount of internal heat sources. In these buildings, the envelope’s heat flow is smaller than in conditioned buildings, for this reason a larger surface area has less impact on the indoor temperature. (Givoni, 1994)

According to Wood and Salib, (2013 ) ), referring to the historical evolution of the form of high-rise buildings, the high cost of electricity and the need to conduct tasks under natural lighting conditions had a profound impact on the design of office buildings. The need to provide adequate daylight, limited the depth of office floor plans, and consequently enabled natural ventilation by means of operable windows. Natural ventilation was also considered necessary for sanitary purposes and for eliminating excessive humidity. The building forms were also influenced by classical styles of architecture with central open courts, that limited plan depths to let natural light and air into the interior.

By the 1950s, the ability to control indoor temperature and humidity by mechanical systems eliminated the restrictions regarding the floor plan shape and plan depth. Relying on air-conditioning allowed the emergence of deep-planned, transparent office buildings with curtain-walled windows. (Wood and Salib, 2013)
6.5 BUILDING ENVELOPE

The building envelope is the barrier that separates the indoor space from the outdoors. It keeps rain, wind, heat, cold, light, and noise from entering the indoors. Walls, floor slabs, and balconies can affect the light and thermal performance of the envelope. Balconies are common in residential buildings, however, in extreme climatic conditions they can form thermal bridges if not properly thermally protected. (Syed, 2012)

A high-performance envelope helps to reduce energy use in buildings. The components that make up the envelope are walls, glazing, Mullions, roofs, skylights, doors, windows, and slab edge insulation (Syed, 2012). There is no universal definition for a high-performance envelope, but it could be defined as one that performs better than the mandatory energy code requires, while consuming less energy than the mandated energy code allows. (Syed, 2012)

Glass is a significant contributor to energy consumption in buildings. According to Syed, (2012), about 25% to 35% of energy consumed by buildings is due to the use of glass. About 10% of the total carbon emissions in the United States can be attributed to glass. (Syed, 2012)

Studies for low energy high-rise buildings in cities built in climates similar to Athens like Izmir, Portugal and other regions of southern Europe (Raji, Tenpierik and van den Dobbelsteen, 2016) have shown that the most important parameters that might be worth optimizing in a building located in such climate are: air-infiltration, aspect ratio of the building, cooling set point temperature, window area, glazing properties, shading, wall and roof type, mechanical ventilation rate (fig 6.7). (Raji, Tenpierik and van den Dobbelsteen, 2016)

<table>
<thead>
<tr>
<th>STUDIES</th>
<th>Yıldız and Arsan</th>
<th>Capeluto and Ochoa</th>
<th>Tavannes and Martins</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESEARCH GOAL</td>
<td>most influential design variables for energy consumption in apartments</td>
<td>ranking of energy efficiency solutions</td>
<td>optimization of design parameters of a public building</td>
</tr>
<tr>
<td>LOCATION</td>
<td>İzmir, Turkey</td>
<td>13 urban centers from North to South Europe</td>
<td>Portugal</td>
</tr>
<tr>
<td>MOST INFLUENTIAL VARIABLES</td>
<td>- air infiltration</td>
<td>for South Europe</td>
<td>- wall type</td>
</tr>
<tr>
<td></td>
<td>- aspect ratio of building</td>
<td>- improved shading</td>
<td>- roof type</td>
</tr>
<tr>
<td></td>
<td>- cooling set point</td>
<td>- glazing</td>
<td>- window frame</td>
</tr>
<tr>
<td></td>
<td>- window area</td>
<td>- glazing</td>
<td>- glass type</td>
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<tr>
<td></td>
<td></td>
<td>- shading</td>
<td>- HVAC system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- infiltration rate</td>
<td>- mechanical ventilation rate</td>
</tr>
</tbody>
</table>

Factors that can be considered for selection of window-to-wall ratio of a facade are the ability to provide adequate daylight into the space, the reduction in electricity demand for lighting and the impact on peak heating and cooling demand and energy consumption. (Tzempelikos, Athienitis and Karava, 2007). According to Tzempelikos et al., (2007), large fenestration areas often result in excessive solar gains and highly varying heating and cooling loads. Additionally, intense daylight leads to glare problems, especially for south-facing facades of office buildings.

Requirements for energy efficiency in envelope elements are normally based on resistance to heat transfer through a material (R-values) or a value for thermal transmittance (U-value). Thermal transmittance is the rate of heat flow through a unit surface area of a component with unit (1K) temperature difference between the surfaces of the two sides of the component. It is often called the Overall Heat Transfer Coefficient, U-value, and is expressed in W/m²K. (Al-Homoud, 2005)

The proper use of thermal insulation in buildings contributes in reducing the required air-conditioning system size and also in reducing the energy cost. Furthermore, it extends the periods of thermal comfort without reliance on mechanical air-conditioning especially during inter-seasons periods. (Al-Homoud, 2005) According to Al-Homoud, (2005), the best performance can be achieved by placing the insulating material close to the point of entry of heat flow. This means placement of insulation to the inside for climates in which winter heating is dominant and to the outside for climates with increased cooling loads.

Thermal insulating materials resist heat flow with the aid of the numerous microscopic cells, which suppress convective heat transfer. The air trapped within the insulation provides the thermal resistance, not the insulation material. Typically, air-based insulation materials cannot exceed the R-value of still air. However, plastic foam insulations (e.g., polystyrene and polyurethane) use fluorocarbon gas (heavier than air) instead of air within the insulation cells, which gives higher R-value. (Al-Homoud, 2005)

Many types of building thermal insulation available on the market fall under the following basic materials and composites categories (Al-Homoud, 2005).

Inorganic Materials
- Fibrous materials like glass, rock, and slag wool.
- Cellular materials like calcium silicate, bonded perlite, vermiculite, and ceramic products.

Organic Materials
- Fibrous materials like cellulose, cotton, wood, pulp, cane, or synthetic fibers.
- Cellular materials like cork, foamed rubber, polystyrene, polyethylene, polyurethane, polysiocyanurate and other polymers.

Metallic or metallized reflective membranes
These must face an air-filled, gas-filled, or evacuated space to be effective.

Reflective insulation
Reflective insulation reduces heat transfer by radiation. It uses larger air spaces, than other insulation types, faced with foil on one or both sides. Reflective insulation is most effective in hot climates with increased cooling loads. A radiation barrier can be placed under the roof to reduce radiant solar heat gain from the sun or in west or east walls receiving direct sun radiation. (Al-Homoud, 2005)
WALL AIR TIGHTNESS

Infiltration can have a significant impact on the energy demand. Infiltration is dependent on the tightness of the building construction, exterior shielding, temperature differences, wind velocity, and building height. On the contrary, in order to tackle problems associated with well insulated tight buildings such as poor indoor air quality and moisture accumulation, it is important to provide adequate ventilation. Ventilation can prevent moisture condensation on window surfaces as well as concealed condensation within walls and roofs during the heating season. (Al-Homoud, 2005)

FLOOR AND ROOF CONSTRUCTION (THERMAL MASS)

Thermal mass reduces instantaneous thermal loads by absorbing a portion of the load and releasing it at a later time. Thus, the building’s peak cooling load is offset. (Syed, 2012) Reduction in peak loads is associated with the reduction in instantaneous demand for electrical power within the peak demand zone. Thus, high costs of upgrading the utility infrastructure to meet the peak demand can be avoided. (Syed, 2012)

When the thermal mass of the building engages with a diurnal (24 hour) cycle, the heat from the daytime solar energy can be stored and released during the night for heating. For example, in colder climates the building mass can absorb the heat during the daytime hours, store it, and transfer it in the nighttime colder hours. For this, materials with high density and optimum thermal conductivity like concrete are required. Low conductivity is a disadvantage, as it takes too much time to store heat. Moreover, regarding thermal mass on the envelope, placing the insulation between the thermal mass and the indoors reduces the effect of thermal mass. (Syed, 2012)

GLAZING U-VALUE/FRAME U VALUE

U-value is a measure of heat transmission from one side of the glass to the other. The lower the U-value, the lower the heat transfer rate. The U-value depends on the thickness of the glass, the number of panes in the assembly, the spacing between the panes, the type of gas or vacuum between the panes and on the coatings used on the glass (low-E coatings). Glazing U-value is the U-value of the center glass itself, and does not include any heat loss from the frame. The glass decisions should be made not just by glass U-values, but the combined assembly of glass and Frame U-values. (Syed, 2012)

GLAZING (G-VALUE)

The solar heat gain coefficient is the fraction of heat from the sun that enters the envelope through the glazing. The lower the G-value, the less energy enters the building. In Europe, the metrics to express this coefficient is the G-value, and in America is the SHGC (solar heat gain coefficient). The difference between G-value and SHGC is that they use a different value for air mass. The G-value of glass is reduced be adding color tints or reflective coatings. Selecting the heat gain coefficient means balancing between summer benefits and winter losses. Low solar coatings work well in hot climates. (Syed, 2012)

GLAZING (LSC LIGHT TO SOLAR GAIN RATIO)

Light to solar gain ratio (LSG) is the LST value divided by the SHGC value. A higher LSG is indicative of lower solar heat gain and higher visible light transmittance. To achieve a higher LSG, spectrally selective and tinted glasses can be used. (Syed, 2012)

SOLAR SHADING

One way of blocking unwelcome solar radiation the use of shading devices. Considering its position with regard to the indoor environment, they can be classified as exterior and interior systems. External shading is more effective than internal, but entails higher maintenance. (Konstantinou, 2014) The orientation is also an important factor that determines the type of shading. Horizontal solar screening louvers block direct sunlight on the south with unobstructed view to the outside. On east and west facades, where the sun strikes at low altitudes, movable vertical louvers are preferred, that block the sun but can allow for some view. (Hausladen et al., 2006)

EXTERNAL SYSTEMS

Normally external sunshading devices are major architectural features and can even constitute an important determinant on the building aesthetics. Their location enables them to block solar radiation before it reaches the envelope, hence less heat solar gains in the building. Due to their exposition to environmental conditions, their initial and maintenance costs are high (Hausladen et al., 2006). These systems can also be fixed or operable. The degree of operability is variable, some devices can be operated by the user, whilst others by the building management system. Examples of external systems are: vertical/horizontal louvres, venetian blinds or overhangs. (fig. 6.8)

Source: ArchDaily, 2017

Figure 6.8: external sun shading types

INTERNAL SYSTEMS

Due to their location inside the building, their solar shading effect is much less than of the exterior systems. Additionally, these systems can heat up and emit solar radiation to the space, which would reduce the indoor comfort. Nevertheless, they are protected from the weather conditions, hence their initial and maintenance costs are considerably lower than that of exterior devices, which constitutes their main advantage (Hausladen et al., 2006).

SHADING CONTROL

According to Tsampelikos et. al., (2007) appropriate shading design and control, when linked with simultaneous control of electric lighting and HVAC components, could significantly reduce peak cooling load and energy consumption for lighting and cooling, while maintaining good thermal and illuminance indoor conditions.
Passive ventilation of a building is possible with natural ventilation. Natural ventilation through the facade's openings is driven by the climatic forces of wind (wind effect) and temperature (stack effect). Thus changes of wind pattern and temperature can affect the natural ventilation performance (Hausladen et al., 2006). The cooling effect of air speed and psychological factor allow thermal comfort in a higher range of temperatures when natural ventilation is present. (ASHRAE, 2010)

A ventilation strategy refers to how air is introduced into a building and how it is extracted out of it. For high-rise buildings, natural ventilation can be classified into three main categories: Single-sided ventilation, Cross-ventilation and Stack-ventilation. (Wood and Salib, 2013) Apart from natural ventilation, mechanical ventilation and mixed mode ventilation systems are used in high-rise buildings.

**SINGLE-SIDED VENTILATION**

Fresh air enters the room through the opening on the same side it is exhausted from. This strategy can effectively ventilate a space with room depth maximum 2.5 times its height. (Wood and Salib, 2013)

**CROSS-VENTILATION**

It relies on the flow of air between the two sides of a building’s envelope due to the pressure difference between the two sides. For effective cross-ventilation, the depth of the room must not exceed 5 times its height. (Wood and Salib, 2013)

**STACK-VENTILATION**

Fresh air enters into the building at a low level and it is exhausted at a higher level due to temperature differences between the interior and exterior or between certain zones within a building. Stack ventilation is often used in buildings which have a central atrium or chimney. (Wood and Salib, 2013)

**MIXED-MODE VENTILATION**

Depending on the climatic conditions of a building site, as for example the climate of Athens, it may not be possible to rely solely on natural ventilation. In this case, mixed-mode ventilation that utilizes a combination of natural ventilation and mechanical systems is used. Mixed-mode ventilation can be either zoned or complementary. Zoned is where mechanical cooling and natural ventilation operate in different areas of the building. Complementary is where the building is designed with the capability to operate under mechanical and natural ventilation modes in the same space. (Wood and Salib, 2013)

**6.6 BUILDING SYSTEMS (HVAC)**

Active building systems play a supplemental role in areas where passive systems are not enough. In order to achieve a nearly zero energy building, building systems should be integrated to the overall design of the building for maximizing reduction of energy consumption and emissions. Combined heat and power systems, heat pump systems, storage techniques, condensing boiler installations and similar systems are widely used in standard practice currently.

According to greek regulations (KENAK), the minimum specifications for the building’s electromechanical installations, include heat recovery by at least 50% in central air-handling-units with fresh air supply greater than 60%. Energy efficient lighting with proper central control in non-residential buildings, thermostatic control in different thermal zones, independent heating and cooling with heat meters, power factor correction in non-residential buildings are also requirements. Moreover according to the current Greek law (KENAK) it is advisable to use building management systems (BMS) and combined heat and power systems for the large commercial buildings that have high thermal loads.

**HEATING SYSTEM: GEOTHERMAL HEAT PUMPS / HEAT RECOVERY / HEATING SET-POINT**

Current greek regulations (KENAK) suggest to use geothermal heat pumps for heating with coefficients COP>=4.5 and EER<= 4.0. The law indicates, heat pumps in heating mode must have a COP>= 3.2 if air cooled and >= 4.3 if water-cooled.

**COOLING SYSTEM: GEOTHERMAL HEAT PUMPS / COOLING SET-POINT**

KENAK advises to use geothermal heat pumps for cooling with coefficients COP>=4.5 and EER<= 4.0. Greek regulations indicate, heat pumps in cooling mode must have an EER>= 2.8 if air-cooled and >= 3.8 if water-cooled. The cooling set-point for the climate of Athens, Greece is set to 26 °C.

**AIR DISTRIBUTION**

A variable air volume (VAV) system helps meeting the indoor air quality standards by supplying a minimum amount of fresh air based on national regulations and standards. When cooling is needed, the thermal comfort is met by increasing the air flow and supplying enough colder air than the room temperature. When the heat load
increases in a zone controlled by a VAV system, the flow increases. A room controller, that measures the room air temperature and the supply air flow, controls the air flow to the room. The supply air flow depends on the load and temperature difference between the zone and the supply air. (Engdahl and Johansson, 2004)

Inoue and Matsumoto (1979) have made energy analyses of the VAV system and compared it with other systems such as dual duct constant air volume (CAV) and two-pipe induction unit. With Tokyo weather data, the VAV system had the lowest cooling coil load and lowest annual fan energy use. (Engdahl and Johansson, 2004)

A VAV system utilizes individual flow control boxes which control the air flow from a main supply duct into an individual zone of a building. The air flow is controlled by moving a damper or valve in the flow control box.

**LIGHTING-EQUIPMENT (EFFICIENCY/ BMS)**

Increased efficiency of lighting and appliances can lead to reduced energy use. Apart from efficiency, user patterns that determine the energy use, can be improved by efficient controls and switches. (Konstantinou, 2014)

Artificial lighting is also responsible for increased internal gains and thus affect heating and cooling loads. Common luminaries have a power density around 5.00 and 6.00 \([\text{W/m}^2 - \text{100 lux}]\). More energy efficient lighting types are for example LEDs with 2.5 \([\text{W/m}^2 - \text{100 lux}]\).

**6.7 RENEWABLE ENERGY**

As the density of urban development increases, buildings become more concentrated and increase in height. Solar energy systems can therefore have a substantial role in compensating for the increasing energy demands of high-rise buildings in Europe. Currently there are a lot of different systems available that use sunlight to produce energy. Most of them are rectangular panels that can be directly mounted on a surface, as a facade or a roof, or mounted on an optimal angle. In this review the focus is on electricity producing systems that can be easily integrated in the envelope of high-rise buildings, which limits the scope to static photovoltaic systems (PV).

**SOLAR RADIANCE AS ENERGY INPUT**

The energy output of a solar energy system depends mainly on the solar energy available. The parameters of the solar gains are firstly according to Roberts, Guariento, (2009) the direct irradiance, which is dependent on the sun’s position and the sun’s path tracing a range of angles through the day and year. Secondly the diffuse irradiance, which arrives at a surface from clouds and haze, and also makes a contribution to PV output. On a clear day, direct solar irradiance makes of approximately 80\% of the total solar energy reaching the earth. On a cloudy or foggy day solar irradiance is minimized.

**OPTIMAL TILT ANGLE AND ORIENTATION FOR SOLAR ENERGY COLLECTION**

For non-tracking solar collector systems the orientation and the inclination of the system need to be taken into account.

**ORIENTATION**

The orientation of the PV system is based on the azimuth angle (fig. 6.13), which is the direction of the incoming sunlight. The azimuth angle depends on the horizontal direction of the sun and a reference plane. At solar noon, the sun is always directly south in the northern hemisphere.
INCLINATION
The inclination or tilt angle is related to the elevation angle of the sun. The elevation angle is the angular height of the sun in the sky and the horizontal. At sunrise, the angle is 0°, when the sun is directly overhead, it is 90°. (Roberts, Guariento, 2009) The maximum intensity occurs when the sun’s rays arrive perpendicular to the surface of the system. For the calculation of the sun’s position throughout the day, the elevation and azimuth angle must be calculated throughout the day and can be presented by a sun path diagram. These angles are illustrated in Figure 5.14. Those parameters depend on the latitude and the corresponding sun paths. (Roberts, Guariento, 2009)

NON-OPTIMAL TILT AND ORIENTATION
In contrast to a ground or roof mounted PV system, BIPV (Building integrated photovoltaics) may be subject to non-optimal orientations (Roberts, Guariento. 2009). For the possible orientation of the PV modules, global insolation charts can be used for the construction site. A useful quantity is the average daily insolation, in energy units kWh. Daily insolation varies through the year, increasing with day length and altitude of the sun. Figure 6.15 illustrates the daily global horizontal solar radiation. These charts combine the direct and diffuse irradiance for typical annual weather at a given location. From the insolation charts, it is visible that the vertical angle is more important for the performance whereas the orientation anywhere between southeast and southwest can vary.

PV MATERIALS AND CELLS
The basic element of a PV system is the photovoltaic cell. The cells linked together create a module. The system is comprised of PV modules that are connected together. The PV energy production works by the photovoltaic effect in semiconductor materials. With metal contacts on the top and bottom of the PV cell, current is generated and can pass through the external circuit.

Crystalline solar cells are the most commonly used cells. Single-crystal silicon PV cells (fig. 6.16) are available on the market with efficiencies close to 20%. Polycrystalline silicon cells (Figure 6.17) are produced easier and more cost effectively. They are used widely because they have marginally lower efficiency than the single-crystal cells. Gallium arsenide (GaAs) is another single-crystal material used for the production of high efficiency solar cells.

BUILDING INTEGRATION OF PHOTOVOLTAIC SYSTEMS
PV elements can also have the same role as a wall, window or roof cladding. Therefore, the applied system needs to achieve the required level of air-tightness and weather-tightness, daylight, and ventilation, in order to create a comfortable indoor environment while using minimum amount of energy. Additionally, BIPV building-envelopes need to withstand the corresponding load cases.

BIPV PRODUCTS
BIPV module products and solar cell glazing products are most commonly used for this purpose (Jelle, et al., 2012).

-BIPV module products:
These replace various types of roofing and the mounting systems and are easy to install. Some of the BIPV module products are factory-made modules with thermal insulation. This material is less cost effective than silicon, which restricts its use to concentrator and space applications. (Sick and Erge, 2014)
Figure 6.18: Example of BIPV module products from Creaton AG (left) and Rheinzink

- **BIPV solar cell glazing products:** They provide options for windows, glassed or tiled facades and roofs. Options on colours and transparencies provide a variation of aesthetic results. The solar cell glazing modules provide both shading and natural lighting to the building. The distance between the solar cells can vary according to the wanted transparency level. (Jelle, et al., 2012)

Figure 6.19: Example of various solar cell glazing products from Sapa Building System
Source: (Jelle, et al., 2012)

The offered BIPV products can have different integration opportunities at the building envelope. The main architectural application typologies selected for the scope of this report are BIPV installation as facades and roofs (fig. 5.22). Facades have a wide spectrum of applications such as rain screens, curtain walls and shading systems. (Jelle, et al., 2012)

**BIPV IMPLEMENTATION IN BUILDING DESIGN**

- **Rain-screen cladding** (fig. 6.21) forms an outer skin and offers weather resistance with water and air barriers that are separated by a drained and ventilated air void. Ventilation lowers the temperature of the PV cells, which increases the power efficiency. This approach can be used on new buildings or building renovations. These panels are mounted onto cladding rails that are attached to the building. (Roberts, Guariento. 2009)

- **Curtain wall** systems (fig. 6.22) incorporate photovoltaic cells with double glazed units. These units comprise an outer laminated glass- PV-resin-glass pane and an inner glass pane with a sealed air gap between. This system combines the energy efficiency of double glazing with a solar power source. The arrangement of the cells within a panel can be varied to control the ratio of light passing through the panels. (Roberts, Guariento. 2009)

- **Shading systems,** with BIPV as incorporated shading devices (fig 6.23), can provide large vision areas and protection from direct daylight for the occupants of the building. These shades can be fixed or adjustable. The application of PV cells as shading systems has the advantages of maximizing the incident solar energy when the shadings are movable and the surface area for PV cells can be wider than that of the vertical surfaces. The movable shading systems can use power from the solar cells for angle adjustments. (Roberts, Guariento. 2009)

- **Roof mounted** PV systems can serve as a skylight for the building (fig. 6.24). The PV panels are mounted into a system of an inclined structure with single or double glazing, optimally orientated to the sun. The roof mounted systems are mostly used for locations closer to the equator where sunlight vertical to the earth surface is most predominant. The combination of skylights with BIPV with south orientation and glazing of northern orientation, provide to the building natural lighting and energy gains. PV arrays can also be mounted onto most existing roofs without being part of an integrated building design. (Roberts, Guariento. 2009)
This chapter focuses on the simulation and optimization of the shape, orientation and design and construction elements of a high-rise open plan office building in Athens, Greece. The results from this study will determine which parameters are the most influential regarding the reduction of the energy consumed by the building and the thermal comfort levels. The parameters have been selected based on the previous literature review.

As a starting point for the different optimization steps, a building in the port of Athens, Piraeus, is selected. The floor plan area of the building and the ratio between the office area and the core area are the design constraints for the first optimization step of the shape of a high-rise building. The optimization steps consist of three steps. The first step is the optimization of the shape of the floor plan. The second step is the optimization of the orientation of the building. The third step is about the integrated optimization of the design and construction elements of the envelope of the building, the HVAC systems and the energy generation from renewable energy sources.

The first 2 optimization steps for the shape and orientation are implemented with simulations in Design Builder. The comparison between different options of shape and orientation is done with the aim of finding out the most optimal design with the lower Annual Site Energy Use Intensity (EUI). The results are an indication of the amount of effect on EUI the different shapes and orientations have. For the simulations in Design Builder, a simplified model of a high-rise building is created in order to reduce the simulation time.

After the analysis of these results, a building with a defined shape and orientation is further optimized in the third step. For the 3rd step, 2 separate multi-objective optimizations are implemented. The 1st optimization involves design and construction parameters, HVAC system elements and energy produced by photovoltaic panels integrated on the building serve as the variables for the optimization.

After this optimization, the optimal design chosen is further optimized according to window to wall ratio and shading area per facade orientation. The simulations are implemented with Energy Plus through Grasshopper via the plug-in Honeybee. For the optimization, Grasshopper is connected with modeFRONTIER in order to post-process the various generated design and construction options and establish the influence of the different variables on the EUI and adaptive thermal comfort levels of the building. As a result for this stage, a certain design is chosen that is balanced between EUI and thermal comfort levels. The variables entailed in this design serve as a starting point in defining the strategies towards the design of a high-rise open plan office building that could be potentially nearly zero energy in Athens, Greece.
The tower of Piraeus is selected as a case study building, in order to have a design reference as a starting point for the optimization. This building is selected because it is an open plan office high-rise building with a core in its center and useable open office space in the peripheral floor plan, with repeating floor plans.

Located in the port of Piraeus in Athens, Greece, the Piraeus Tower is the second tallest building in Greece. This building has been abandoned for more than 30 years. It is a 22-storey building of 84m height and is the only high-rise building in one of the biggest ports of the Mediterranean area which has a dynamic financial growth the last decades.

The construction of the building started in 1972 by the architects: Vikelas, Molfesis and Loizos. In 1983 the exterior facade was finished which is made out of steel and glass. Only three floors of the base of the tower were ever used since its completion for commercial use, educational use and for public services. The rest of the building has always remained unused. The tower consists of a 45.42x27.26 m rectangular floor plan. The bearing structure is made out of steel reinforced concrete.

Architects: Vikelas, Molfesis and Loizos
Structural engineer: Oikomomou
Floors above ground: 22
Floors below ground: 2
Floor plan area: 1034.35m²
Height until last occupied floor plan slab: 80.10m
Structural material: concrete
7.2 GEOMETRY OPTIMIZATION

7.2.1 DESIGN BUILDER BUILDING MODEL

Transitioning from the case study design to the simulation model in Design Builder, several simplifications need to be implemented with the goal to save simulation time, but at the same time it remains accurate enough. The building floor plan in the simulation model remains an open floor plan as in the built reference. The existing building has 2 cores for circulation and restrooms and a corridor between the two cores. For the simulation, the area of the 2 cores and the corridor is simulated as 1 closed core area.

The height of the simulation model is 101m as a high-rise building according to the definition of high-rise building aforementioned in the literature study. The model consists of 31 floors of 3.26m height as in the case study building. Additionally, to reduce the simulation time, adiabatic component blocks are generated, instead of typical floor plans. The high-rise building model simulates 3 levels: the ground floor, the intermediate middle floor and the last floor with the roof. The intermediate floor represents a typical floor plan. The energy calculations of this floor plan are used in the zone multiplier command as a reference for the loads of all the intermediate floor plans simplified as adiabatic blocks. This is done to approximate the calculations referring to the whole building, but decrease the simulation time. The thermal and radiance daylight calculations from the core area are not taken into account in the simulations, since it’s an enclosed space dedicated to circulation, with the same floor plan area for all the examples and will not affect the final comparison of the energy loads for choosing the optimal shape.

The following input data are used to run the simulations and are based on the current national standards of Greece for the design and construction of office buildings as explained in chapter 2.3. The simulations are made for an annual period from January 1st until December 31st. Internal floors and internal partitions for core are created adiabatic.

**WEATHER DATA FILE**

The weather file contains hourly weather data from the weather data report “GRC_ATHENS_IWEC” for the researched location. The weather data used for this research are epw files retrieved from the data base of Design Builder for the city of Athens, measured at the area of Helliniko, an area located near the sea in the city of Athens, with similar climate and geographical characteristics to the port of Piraeus.

**Site Location:**
- Latitude (°): 37.90
- Longitude (°): 23.73

**MODEL INPUT**

Site Location:
- Latitude (°): 37.90
- Longitude (°): 23.73

The weather file contains hourly weather data from the weather data report “GRC_ATHENS_IWEC” for the researched location. The weather data used for this research are epw files retrieved from the data base of Design Builder for the city of Athens, measured at the area of Helliniko, an area located near the sea in the city of Athens, with similar climate and geographical characteristics to the port of Piraeus.
7.2.2 SHAPE OPTIMIZATION

The floor plan shape of a high-rise building with repetitive floor plans, defines the geometry of the building to a large extent. The design of the geometry of the floor plan derives not only from energy considerations, but from economic, aesthetic and functional considerations.

The first step of the optimization strategy is the optimization of the shape of the building. This is realized by keeping the floor plan area constrained, while gradually changing the shape from the floor plan from a more compact shape like the octagon, to a more elongated rectangular shape. Aim of this optimization step is to define which floor plan shape leads to a more reduced energy consumption and also to define the extent of influence of the floor plan shape in the energy consumption of a high-rise open plan office building, with mixed mode ventilation system in Athens, Greece.

7.2.3 FROM THE CASE STUDY TO THE DESIGN BUILDER MODELS

The following parameters in the floor plan shape optimization remain constrained:

- area of the 2 service cores: 188 m² (18.2% of the total area)
- total floor plan area: 1034 m²

Due to the fact that the single central core of the Design Builder models is located in the center of the floor plan, the corridor area varies as it would in a realistic design of a building. Therefore the service core area varies due to the corridor variation in the different floor plan shapes.

The floor plan depth for the rectangular, square and octagon shapes is approximately 8.2m, whereas for the elongated rectangular, the floor plan depths is minimized to 6.3m, since the core should have realistic dimensions to fit the elevators, stairs and WC.

The DesignBuilder models with floor plan differentiations were created with the aforementioned simplifications and simulated with the above mentioned inputs.
RESULTS

Figures 7.10, 7.11 and 7.12 show the results for the cooling, heating and lighting loads of the various floor plans for the shape optimization step. It is evident from the results that cooling loads and lighting loads are the source of intensive energy consumption, whereas heating loads are nearly zero due to the high temperatures of Athens not only in the summer but during most of the year.

Regarding the cooling loads, as it is illustrated, compact buildings are favorable in reducing energy consumption for cooling.

Heating loads are nearly zero regarding the annual demands, so the ranking of the floor plan shape does not necessarily illustrate a trend towards a more compact or a more elongated shape for the aforementioned climatic conditions.

Lighting loads seem relatively more diminished in the case of the elongated rectangular shape, whereas for the rest of the shapes the aspect ratio of the building seems to play no role. What seems to be important though is the orientation of the longer-sized and smaller-sized facades.

As it is visible from the annual total site energy, the differences in energy consumption among the different buildings are minimal. The elongated rectangular building is the best performing building with a value of 86.7 kWh/m² of annual energy use intensity and the worst performing building is the one with the square layout with approximately 87.4 kWh/m². The differences are due to the different effects of plan shape on lighting and cooling loads. From the graph it is evident that the effect of the aspect ratio of the layout of a high-rise open plan office building, that has a mixed mode ventilation system and with the specific climatic characteristic, is negligible, therefore a designer could be free to explore more options by prioritizing aspects of structural, aesthetic or functional optimization.

The following graphs illustrate the results (fig. 7.14) illustrate the relation between cooling loads and solar gains. In the graphs for cooling loads ranking and solar gains ranking, a strong correlation is visible between the increase in cooling loads with the increase of solar gains. It is safe to derive out of this correlation, that more compact shapes with minimized facade surface lead to minimized solar gains and therefore to minimized cooling loads. Furthermore, the building is actively cooled. So, the indoor air temperature is often below the outdoor temperature. The more compact the shape, the lower the heat transfer and thus the lower the cooling load.

The graphs (fig. 7.15) shows that the elongated rectangular shape performs better than the other shapes in terms of daylight efficiency. Nevertheless, the elongated rectangular has a shorter facade depth of 6.3m as opposed to the rest of the shapes that have a floor plan depth of 8.2m. This is due to the fact that the floor plan area and the core area remain constrained, but the core area that is located in the center of the building should have realistic dimensions. Therefore, the way that these models with the different aspect ratios and core sizes were created serve for more accurate thermal optimization. On the other side, out of this restriction, it was made possible to see how important the floor plant depth is in a building for the exploitation of daylight and the reduction of artificial lighting. Therefore, buildings with reduced floor plan depth can have reduced lighting loads. One such example is the Kommerzbank high-rise office building in Frankfurt, with floor plan depth of 7.5m and an atrium with skygardens that allows daylight access also to the offices overlooking at the atrium.

As for the lighting loads of the rectangular, square, and octagon shape, it is clear that shapes that have smaller facades facing the south are exploiting the daylight more efficiently. That happens since when the solar radiation comes from the south direction at late morning until early afternoon, the inclination of the solar radiation especially for southern countries falls at a bigger incidence angle and thus does not reach at the deepest point of the floor plan.
7.2.3 ORIENTATION OPTIMIZATION

From the previous optimization step it is manifest that neither of the above shapes will drastically change the energy consumption of the high-rise building. Additionally, for compact shapes of floor plans like the square or the octagon, changing the orientation will have little effect on the energy consumption. Also the elongated rectangular shape that is relatively better performing, has a shorter floor-plan depth of 6.3m, which is less than many reference high-rise buildings like the Kommerzbank high-rise building in Frankfurt. Therefore, for the orientation optimization, the rectangular shape is chosen that is also the shape of the case study building in the port of Piraeus.

For this step 4 different orientations of the rectangular shape are analysed. The orientations are: North-South, East-West and Northwest-Southeast, Southwest-Northeast with a rotation angle of 45°.

For the simulations, the same DesignBuilder model with the previous optimization step is used, along with the same inputs that refer to the current national standards of Greece for the climatic zone that includes the researched site location.

RESULTS

Figures 7.18, 7.19 and 7.20 show the results for the cooling, heating and lighting loads of the various floor plans for the orientation optimization step.

The charts for the cooling loads show no significant differentiation in the amount of cooling loads for different directions. Nevertheless, the existing differences could be attributed to the different exposure on solar radiation.

Regarding the heating loads, heating demands for these climatic conditions are next to zero and therefore the results do not serve for indicating a trend in the direction options of the building.

Lighting loads differentiations are also not significant between different orientations. It also seems that longer facades exposed to the south direction do not make a great difference for daylight exploitation due to the steep incidence angle of the solar radiation from the south.

Subsequently, the annual energy demands of the building are not drastically affected by the orientation. Nevertheless, the building with East-West orientation of the long axis performs slightly better than the rest since it exploits daylight marginally better than the rest orientation.

This step shows that the orientation of a building when there are no surrounding high-rise buildings, only affects to a minor degree the energy consumption within the climatic conditions of Athens. Additionally, the cooling and lighting demands show opposite trends, regarding the ranking of the different orientations.
Seeing the solar gains chart (fig. 7.22), it is evident that greater exposure of the facade towards the east and west directions lead to increased solar gains. On the other hand exposure of the long side of the facade towards the south leads to diminished solar gains due to the fact that the incidence angle of the solar radiation does not let the solar radiation reach deep in the floor plan of the building. On the contrary when solar radiation comes from the east and west, the incidence angle is small so the solar radiation penetrates the whole floor plan, therefore the increased solar gains.

This lighting loads’ chart (fig. 7.23) might be an indication of how the occupancy schedule, in this case an office schedule, might affect the lighting loads of the building. As it is illustrated, orientations that leave the longest facade surfaces exposed towards the East and Southeast direction where the daylight comes in during early morning hours, seem to have increased lighting loads. This could be related to the fact that during early morning hours when the sun rises, the office building has still no occupants. Therefore, the daylight is not exploited as well as in the other orientations, where south and west exposure of the long facades coincides with the south and west solar radiation direction that falls within the working hours.

As a conclusion from the shape and orientation optimization steps, the shape and orientation of a high-rise, mixed mode ventilated, open plan office building do not have drastic effect on the energy consumption of a building in the climatic conditions of Athens, Greece. This is a clear indication that a designer is not highly restricted from an energy consumption point of view, to adopt a certain floor plan shape or orientation. Nevertheless, these optimizations were implemented on a high-rise building with no surrounding buildings and in the climatic conditions of Athens. Surroundings with high-rise buildings at close proximity or different climatic conditions could possibly lead to different conclusions.

For the next optimization step – the envelope design and construction optimization- the rectangular building with East-West orientation of the long axis is chosen. This example refers to the aspect ratio of the case study existing building and the optimal orientation for reduced energy loads.

From the various sources of energy consumption in the building, the equipment is responsible for the biggest share of energy use. Cooling loads, followed by interior lighting loads cover almost 800,000 kWh of the total annual energy use of the building. Finally, heating loads for the climatic conditions of Athens are close to zero for an annual period.

For the next optimization steps, it seems that the goal is to reduce cooling and lighting loads, in order to achieve a less energy consuming building.

The chart of the internal gains (fig. 7.26) shows that gains from equipment and solar gains are primarily responsible for the increased cooling loads of the building. This is a clear indication, that in order to achieve a building that consumes less energy, equipment that produces less heat should be placed in the building and the envelope optimization should aim towards more shading and other strategies that deter the increase of solar gains.
The benefit of an integrated optimization, instead of a stepped strategy of separate optimizations, is that when some variables often have conflicting influence on different energy loads, the integrated optimization may lead to better results. For example, the window to wall ratio can affect the electricity production by PV panels mounted on walls. Additionally, smaller windows may lead to reduced solar heat gains, but may increase the artificial lighting loads. Therefore, optimizing all the variables simultaneously can lead to an optimal design, that would not have been possible to achieve with the stepped strategy. Moreover, an integrated optimization allows for the generation of a large number of designs and thus allows the implementation of sensitivity analysis, in order to detect the amount of impact of the variables on the outputs.

Moreover, at this stage, a multi-objective optimization is implemented. Although reduced energy demands for a building is one of the goals while designing a building, the thermal comfort of the occupants also plays an important role and is also a prerequisite set in the European standards. From literature studies it is manifest that thermal comfort may have a negative effect towards the goal of reducing the energy demand of the building. Therefore, the optimal design must balance between acceptable comfort standards and reduced energy demands.

For this optimization step, the energy and daylight simulations will be run with EnergyPlus through Rhino and Grasshopper software via the plug-in Honeybee and the optimization will be driven by modeFRONTIER with the genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm). DesignBuilder can not currently be connected to this optimization platform, whereas for Grasshopper, a custom node that allows for the coupling of GH and modeFRONTIER, has already been established.
BUILDING ENVELOPE

The building envelope is the boundary between the indoor and outdoor environment. For the parameter study 5 parameters refer to the building envelope. The parameters are the window to wall ratio, the wall U-value, the glazing construction U-value, the air-tightness of the facade. The window to wall ratio and the glazing G value are directly related to the amount of solar heat gains that enter the building due to the openings. For a climate with high cooling loads due to solar heat gains and low heating loads, lower wwr and glazing g-values are expected as an ideal outcome. The window and glazing U-values refer to how well insulated the building is. Good insulation protects the building from the outdoor conditions, but since the building is naturally ventilated for many days of the year, it is not easy to predict the impact of these values on the energy consumption. The air infiltration through the facade has similar benefits as the natural ventilation in these climatic conditions.

Figure 7.28: variable steps for envelope design and construction

<table>
<thead>
<tr>
<th>WWR</th>
<th>30% - 40% - 50% - 60% - 70% - 80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALL U-VALUE</td>
<td>0.1 - 0.2 - 0.3 W/m²K</td>
</tr>
<tr>
<td>GLAZING FRAME U-VALUE</td>
<td>0.6 - 1.2 - 1.8 W/m²K</td>
</tr>
<tr>
<td>GLAZING G-VALUE</td>
<td>0.3 - 0.55 - 0.8 W/m²K</td>
</tr>
<tr>
<td>AIR-TIGHTNESS</td>
<td>0.1 - 0.3 - 0.5 - 0.7 air changes per hour</td>
</tr>
</tbody>
</table>

Figure 7.28: window to wall ratios: from 30% to 80% glazed area

WINDOW TO WALL RATIO
For this variable, 6 different values are researched: 30%, 40%, 50%, 60%, 70%, 80% glazing ratios. A 30% glazing ratio is expected to reduce cooling loads, but increase electricity loads, whereas an 80% glazing ratio is expected to increase cooling loads and decrease electricity loads since it refers to almost a fully glazed facade that allows more daylight in the building. The glazing ratio is the same for all directions for this optimization session.

WALL U-VALUE
For the external wall U-value of the building, 3 different values are simulated: 0.1, 0.2 and 0.3 W/m²K. The 0.1 value refers to well insulated buildings and the 0.3 value to a less insulated building. Nevertheless, even the 0.3 value is even lower than the current national standards of Greece that allow a value of 0.5 W/m²K for this climatic zone. Since the building is naturally ventilated, the protection of the insulation is restrained only for the hours when the windows are not open.

GLAZING FRAME U-VALUE
This U-value refers to the glazing and frame construction of the openings. For the openings’ U-value of the building, 3 different values are simulated: 0.6, 1.2 and 1.8 W/m²K. The 0.6 W/m²K refers to triple glazing, 1.2 W/m²K to high performance double glazing and 1.8 W/m²K to double glazing with a worse performance. Nevertheless, the 1.8 value is lower than the current national standards of Greece that allow a value of 2 W/m²K for glass facade. The building simulated is naturally ventilated and the insulation of the openings is only useful for the time-span that the windows are closed.

GLAZING G-VALUE
For the G-value or solar heat gain coefficient, 3 different values are explored: 0.3, 0.55 and 0.8. The 0.3 value allows the least amount of solar heat gains in the building, whereas a G value of 0.8, allows the most amount of solar heat gains. For the climatic conditions of Athens, with intense solar radiation, smaller solar heat gains are expected to reduce the cooling loads and thus reduce the total energy demand of the building.

AIR-TIGHTNESS
Air-tightness of the facade, or infiltration, allows for heat transfer between indoors and outdoors through the envelope. The rate of the infiltration is investigated in this research with value steps: 0.1, 0.3, 0.5 and 0.7 air changes per hour. Since the building simulated is already naturally ventilated, the amount of influence of the air-tightness can not be easily predicted.
ENERGY GENERATION FROM PHOTOVOLTAIC PANELS

This optimization variable is inextricably linked to the window to wall ratio of the building. It refers to PV panels mounted vertically on all 4 facades of the building. It is obvious that for lower glazing ratios of 30%, higher amounts of electricity will be generated and reversely, for high glazing ratios of 70% and 80%, the least amount of electricity will be produced. Nevertheless, for glazing ratios of 30%, the daylight that infiltrates the building will be reduced compared to an 80% glazing ratio.

PV SURFACE-WWR

30% - 40% - 50% - 60% - 70% - 80%

Figure 7.30: variable steps of photovoltaic surfaces related to window to wall ratio

WEATHER DATA FILE

The weather file contains hourly weather data from the weather data report “GRC_ATHENS_IWEC” for the researched location. The weather data used for this research are epw files retrieved from the data base of Energy Plus for the city of Athens, the same to the weather data used for the DesignBuilder simulations.

Site Location:
Latitude (°): 37.90
Longitude (°): 23.73

HCX SYSTEMS

COOLING SET-POINT

Referring to the building installations, this research focuses on optimizing the cooling set-point. There are 3 variables: 24°C, 26°C and 28°C. The cooling set point refers to the indoor temperature above which the mechanical ventilation system will start working. A value of 24°C is expected to increase the comfort level of the building, but also increase the energy consumption. On the contrary, a value of 28°C degrees is expected to decrease energy consumption and also decrease thermal comfort levels.

COOLING SETPOINT - - - - - - 24°C - 26°C - 28°C

Figure 7.29: variable steps for mechanical ventilation cooling setpoints

7.3.2 GRASSHOPPER DEFINITION

The energy and daylight simulations were implemented with honeybee components through Grasshopper. The Grasshopper (GH) definition consists out of 5 parts: the geometry, the energy and daylight simulation, the simulation settings, the outputs and the connection to modeFRONTIER as illustrated in figure 7.31.

Figure 7.31: the different parts of the grasshopper definition

Figure 7.32: honeybee and ladybug components
MODEL INPUT

The following input data are used to run the simulations and are based on the current national standards of Greece for the design and construction of office buildings. The simulations are made for an annual period from January 1st until December 31st.

SIMULATION SETTINGS
-time steps per hour: 6

ACTIVITY
-occupancy density: 0.1 persons/m²
-computers load: 15 W/m²
-heating set-point: 20 °C
-heating set-back: 15 °C
-cooling set-point: (variable)
-cooling set-back: 30 °C
-minimum fresh air: 8.333 l/s-person=30 m³/h/person

CONSTRUCTION
-air-tightness: (variable)
-external wall U-value: (variable)
-floor U-value: 0.4726 W/m²K
-floor construction: acoustic tile/ 50mm insulation board/ 200mm heavyweight concrete
-internal partition U-value: 2.58 W/m²K
-internal partition construction: 19mm gypsum/ wall air space resistance/ 19mm gypsum

OPENINGS
-wwr: (variable)
-SHGC: (variable)
-U-Value: (variable)

LIGHTING
-normalized power density : 3.2 W/m²-100lux
-lighting control: occupancy schedule

HVC
-natural ventilation: on
-min indoor temp for nv: 21 °C
-max indoor temp for nv: 23 °C
-mechanical ventilation: on
-heat recovery : on
-system: ideal loads

PV
-efficiency: 12%

GEOMETRY

In the geometry part (fig7.33), the floor surfaces, roof surfaces, interior walls and exterior walls are translated into honeybee surfaces. Subsequently, the glazed openings and the shadings are created. All these surfaces are combined into creating 5 different zones: the core zone, the zone facing towards the South, the North zone, the zone overlooking to the West and the East zone. Finally the 5 single zones are connected into one floor plan by finding the adjacencies between the single zones. With this process, the interior walls are automatically detected.

Figure 7.33: translating the geometry into honeybee objects

Figure 7.34: the simulated model of one floor-plan
The interior and exterior walls, floor and roof are initially created as Rhino geometry and then serve as an input for the honeybee surface component (fig 7.35). The floor and ceiling are created as adiabatic surface, since the model is a simplification for a high rise building with repeating floor-plans.

![Figure 7.35: settings for interior and exterior walls, roof and floor](image)

At the exterior wall surfaces, glazing geometry is attributed, with having the glazing ratio as a variable for the optimization (fig 7.36).

![Figure 7.36: glazing surfaces and window to wall ratio variable](image)

The geometry generated from the glazing component serves as a starting point, to define the percentage of shaded area at the shading component. In this case, 50% of the window area is shaded (fig. 7.37). At the shading component, the shading material is defined with reflectance (0.8), transmittance (0.15), emissivity (0.2), thickness of shades and conductivity (fig 7.38). The shading system is 3 exterior vertical blinds that cover 50% of the opening area. Exterior blind were selected due to the fact that the block solar radiation outside the facade and thus have more effect towards reducing cooling loads. Nevertheless, due to maintenance issues, exterior blinds are not widely used in high-rise buildings, but this is one more advantage of using double skin facades that could be beneficial towards reaching the zero-energy target. The shading is controlled according to horizontal solar radiation. The shadings are on if the total (beam and diffuse) horizontal irradiation exceed the setpoint of 120 W/m²(fig 7.38).

![Figure 7.37: settings for percentage of shaded area of openings](image)

All these honeybee surfaces, glazing and shadings are connected into single honeybee zones, which are attributed with an open plan office program (fig 7.39). The core zone has a program for circulation of an office building. Finally all the zones are connected, with an automatic interior wall detection with the zone adjacencies component.

![Figure 7.38: shading material- geometry](image)

![Figure 7.39 making single zones from surfaces and assign programs and finding adjacencies for the separate zones](image)
In this part of the GH definition (fig 7.40), the settings for simulating energy production from pv modules, material construction, infiltration and loads of the building, natural ventilation settings, HVAC settings and cooling set points are established. Moreover, the daylight simulation is implemented, the results of which serve as inputs for the lighting schedules of the building.

The part (fig 7.42) is responsible for calculating the electricity produced by PV panels mounted as vertical surfaces on the facade opaque elements of the building. In the first part of this definition, the area of the exterior walls without the openings is transformed into rectangular surface of the same height (3.26m). Since, with the existing plug-ins in Honeybee it is not possible to apply PV modules on surfaces with openings, the area of the exterior walls without the openings needed to be translated into rectangular surfaces. The area of the surfaces covered in PV modules is a variable directly linked to the glazing ratio applied in the glazing component. After the surfaces have been created, it is important to make sure that the surface normals are facing towards the outside of the building, in order to obtain accurate results of energy production.
After the surfaces have been created, PV modules are applied onto them (fig 7.43). Because the component for this use applies PV modules of surface area of 2.5m² per module, a list must be put as an input to the number of Parallel connected modules, according to the different surfaces areas, in order to have every surface covered with the same percentage of photovoltaic coverage. In this case 80% of the wall surfaces are covered with PV modules. The cells efficiency is set to 12% which is a high commercial efficiency according to the previous literature background. Finally, an inverter that transforms generated electricity is applied with a default efficiency of 90%. The outputs are plugged with the EnergyPlus simulation settings.

ENVELOPE CONSTRUCTION AND HVAC SYSTEMS

In this part (fig. 7.44), the construction material attributes of the floor, roof and exterior wall surfaces are customized. Honeybee surfaces also have default materials, so if no materials are changed, the simulation will still be able to run.

CONSTRUCTION MATERIALS

The exterior wall construction has its R-value, translated into U-value, as a variable to be optimized (fig. 7.45). Note that this construction is a simplified one that Honeybee offers, that the designer can directly change the U-value of the whole structure. The drawback of this component is that it refers mainly to lightweight structures, since it does not calculate the thermal mass of the opaque elements. Nevertheless, high-rise office buildings use predominantly lightweight facades for structural purposes, so the accuracy of the results is not expected to be highly compromised.

EXTERNAL WALL CONSTRUCTION

For the glazing construction, the U value and SHGC (solar heat gain coefficient) serve as variables for the optimization (fig. 7.46). Again this is a simplified component that Grasshopper offers and has no thermal mass. On the other hand, the designer can directly change the U value and SHGC value of the glazing structure. Note that the U value refers to the U-value of the glazing and frame construction and not only the U-value of the glazing.

GLAZING CONSTRUCTION

U value includes frame and glass
The floor and roof construction for this model (fig. 7.47), actually, refer to the interior floors of a high-rise building. Therefore, they both have the same construction. This construction will not be optimized, so the materials they entail are not simplified as with the previous components. This means that the thermal mass of the floors is taken into account for the calculations. The structure consists of a layer of 200mm heavyweight concrete, a layer of 50mm insulation board and a layer of acoustic tiles.

After the materials, the loads of the 4 exterior zones are customized (fig 7.48). If not customized, default setting from the open plan office program or office stairs program are used. The infiltration in air-change per hour serves as a variable. The rest of the loads are set according to the settings used in the previous optimization steps in DesignBuilder: equipment load (15W/m²), lighting density (3.2W/m² per 100 lux), number of people per m² (0.1), ventilation per area (0.0008333 m³/s per m²). The loads for the core remain default.

For the schedule customization, only the lighting schedule changes (fig 7.49) as a result of the daylight simulation that gives as an output the hours that artificial lighting is needed. By default the schedules are set to the open plan office schedules. For the core zone, the lighting schedules remain default, since there are no windows for access to daylight.

The natural ventilation refers to ventilation from openable windows. The schedule of when the windows are open or closed is linked with indoor and outdoor temperatures (fig 7.50). Note that Grasshopper only offers the possibility to calculate natural ventilation when the mechanical ventilation is off. So it refers to a changeover ventilation system, when only one of the two options is on. Furthermore, the settings for controlling natural ventilation are directly linked to the settings for the cooling and heating setpoints of the mechanical ventilation. For this optimization the cooling setpoint has the lowest value at 24 ºC and the heating setpoint is set to 20 ºC according to Greek national standards, so the natural ventilation control is bound between 21 ºC- 23 ºC of indoor temperature. Given a higher range of indoor temperatures for natural ventilation, its effect might be more beneficial towards reducing the cooling loads. The outdoor temperature range that allows natural ventilation is set between 18 ºC and 30 ºC.
Regarding the mechanical ventilation (fig 7.51) and other HVAC systems, EnergyPlus does not offer the possibility to calculate complicated installations. For this, OperStudio simulations must be run. With EnergyPlus, only the "ideal loads" systems can be calculated, which refers to the sum of latent and sensible heat that must be removed from the zones. For the ventilation, enthalpy heat recovery with an efficiency of 80% is applied. The cooling setpoint is a variable for the optimization. The cooling setback is set to 30 °C, the heating setpoint to 20 °C and the heating setback to 15 °C according to previous settings in DesignBuilder and the national standards of Greece.

**DAYLIGHT SIMULATION**

The daylight simulation is applied only to the 4 exterior zones (fig 7.52) that allow daylight access through windows. The shadings must be applied to the daylight settings as a separate geometry. Additionally, the floor surfaces are an input in order to create the grid of test points.

The daylight simulation is responsible for a large portion of the time spent for the overall simulation of the building. In sight of the fact that the number of designs predicted to be generated could potentially be max 1944 designs, according to the number of variables set, the time for daylight simulation was a hindrance towards finishing the optimization process within a reasonable time span. A source of delay for the daylight simulations is the number of test points calculated on the working plane surface (at 75cm height). Therefore the test points were minimized as much as possible, at the expense of accuracy of the results. In hindsight of the results of the optimization, these settings do not drastically compromise the accuracy of the optimization of this particular research.

**SET POINTS**

Figure 7.51: HVAC settings and setpoints

Figure 7.52: floor, shading surfaces and zones for daylight simulation

Figure 7.53: daylight simulation settings
SIMULATION SETTINGS

The simulation settings refer to defining the orientation, weather data, simulation period and simulation outputs for the EnergyPlus simulation (fig. 7.54, 7.55).

The orientation is defined by setting a vector for the north direction (fig. 7.54).

The weather file for the researched location is the file “GRC_ATHENS_IWEC” retrieved from the data base of Energy Plus for the city of Athens, the same to the weather data used for the DesignBuilder simulations. It is important to use the internet link for the weather file, as it is downloaded automatically every time Grasshopper opens, otherwise the optimization coupled with modeFRONTIER will not be possible to run.

The simulation period is set to one whole year (fig. 7.56). The simulation outputs needed for this research are the energy loads of the zones and their comfort metrics. The outputs for the results are on an hourly step. The simulations are run by default at 6 time steps per hour as in the setting in DesignBuilder for this research.

Finally, all the components needed for the EnergyPlus simulation are connected as seen in figure 7.57.

RESULTS-OUTPUTS

In this part of the Grasshopper definition, it is possible to read and visualize the outputs for energy use, energy generation and comfort (fig. 7.58-7.64).

It is possible to generate annual total cooling and heating use or divided by the floor-plan area, to attain annual results per m². From the graphs above, it is evident that cooling loads are predominant as expected for these climatic conditions. Total thermal loads refer to the sum of cooling and heating loads.

The lighting loads refer to kWh or kWh/m² of the artificial light used in the building during one year, for all the zones. It is possible to generate the results separately for every zone.

The equipment loads (fig. 7.62) remain constant for all the variations of designs, since they depend on the surface area of the floor plan, which remains unchanged.
It is important within the boundaries of this research, to calculate the adaptive thermal comfort of the building (fig 7.63), since natural ventilation is present. It is evident that in these climatic conditions, of a country of south Europe with Mediterranean climate, the outdoor temperatures are for a large part of the year within the indoor comfort range. So adaptive comfort calculation with naturally ventilated building is expected to result in increased percentage of time comfortable in comparison to PMV comfort. In order to calculate the adaptive comfort, the air temperature and mean radiant temperature of the indoor spaces calculated by EnergyPlus and the outdoor dry bulb temperature for a whole year from the EPW file serve as inputs. The output needed for this research is the percentage of time at which comfortable conditions occur when the indoor temperature is within the comfort range determined by the prevailing outdoor temperature. The outputs are calculated for a whole year for each zone. For this thesis, only the comfort levels of the zones where office spaces are located, are useful. From these 4 zones, the mean value of comfort is generated.

The produced electricity from the photovoltaic modules from all the exterior wall surfaces for one year are generated as kWh. This amount is finally extracted from the total annual energy uses, in order to find the energy balance of the building.

The last step (fig 7.65) is to sum the energy use for cooling, heating, lighting and equipment loads and from this to extract the energy generated. This annual result in kWh is transformed into kWh/m², to serve as input for modeFRONTIER.

For this part of the definition, certain customizations are needed to be made, according to the variables and specific needs of the project. The 5 variables and their names needed must be set in the python script manually (fig 7.67), otherwise it won’t be possible to pass the information to modeFRONTIER.
Finally, a restrictive situation occurs with the working directory and the number of designs that it allows to be generated (fig 7.68). In this python script, as it was given for the needs of this research, it is possible to generate designs from 0 until 999, which is exactly 1000 designs. For the needs of my thesis and the optimization procedure followed, not more than 1000 designs were needed to be generated. For future optimizations and the need for more than 1000 designs, the script needs to be altered.

**Figure 7.68: script for number of designs allowed in one working directory**

```
import os

# Get the current directory
currentdirectory = os.environ.get('RF_APPL_PATH')

# Get the working directory
WorkingDir = currentdirectory

# Create the script
b = WorkingDir + '\simulations\'+str(b[0])

# Simulate
Inputfile = WorkingDir + '\\' + 'input.dat'
```

**7.3.3 OPTIMIZATION WITH modeFRONTIER**

**WORKFLOW**

The optimization was implemented with modeFRONTIER 2016 update1 version. The number of evaluated designs is 1000. The time needed for the evaluation was 44h and 24min. The evaluation time of 1 design was approximately 2' 40''. The optimization run on an i7-5820K, CPU at 3.3 GHz.

The workflow of the optimization as visualized in the interface of modeFRONTIER (fig 7.69) consists of the inputs, the outputs, the connection to Grasshopper, the Design of Experiments component and the optimization algorithm component. Additionally, objectives need to be set, in order for the optimization procedure to be applied according to an objective. For this research, the objectives are minimizing energy and maximizing comfort.

**Figure 7.69: workflow in modeFRONTIER interface**

**VARIABLES AND STEPS**

The user needs to manually apply the variables’ lower and upper boundaries and the number of intermediate steps between the boundaries (fig 7.70), before starting the optimization. The overall number of possible designs is related to the number of values of the variables. All possible combinations of designs if sampling was applied would be 1944 different designs. But, since an optimization is applied, the generated designs do not reach this number, since the optimal solution is found earlier in the process.

**Figure 7.70: setting the variables’ steps and boundaries**

<table>
<thead>
<tr>
<th>Name</th>
<th>Variable Type</th>
<th>Default Value</th>
<th>Expression</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Central Value</th>
<th>Delta Value</th>
<th>Base Value</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>wall_U</td>
<td>Variable</td>
<td>-1.9</td>
<td>0.1</td>
<td>0.3</td>
<td>0.0000000000</td>
<td>0.00000000</td>
<td>0.000000</td>
<td>0.2</td>
</tr>
<tr>
<td>1</td>
<td>glass_U</td>
<td>Variable</td>
<td>-1.9</td>
<td>0.1</td>
<td>1.8</td>
<td>1.287964445</td>
<td>0.99999999</td>
<td>0.000000</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>infiltration</td>
<td>Variable</td>
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<td>0.1</td>
<td>0.7</td>
<td>0.399999997</td>
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<td>4</td>
<td>0.2</td>
</tr>
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<td>3</td>
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<td>-1.9</td>
<td>24.0</td>
<td>26.0</td>
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<td>2.9</td>
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<td>2.0</td>
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<tr>
<td>4</td>
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<td>Variable</td>
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<td>0.5</td>
<td>0.8</td>
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</tr>
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<td>5</td>
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<td>Variable</td>
<td>-1.9</td>
<td>0.2</td>
<td>0.8</td>
<td>0.55799999</td>
<td>0.25</td>
<td>6</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The design of experiments component contains various space filler methods. According to aforementioned literature study, Uniform Latin Hypercube can be used to generate a number of designs with randomly assigned variables (fig 7.71). This serves as a starting point or as the first generation in order to start the process of optimization out of this generation. For this optimization, 25 designs were generated as a starting point. Finding the optimal settings for the optimization like the number of initial designs means that the optimization process must be optimized for finding results quicker and creating an adequate sample of designs for post-processing. Optimizing these settings though is out of the scope of this thesis. Therefore, as a safety factor, these settings are calculated to generate more designs that could potentially be needed.

**DESIGN OF EXPERIMENTS (DOE)**

The optimization algorithm drives the optimization towards creating designs that satisfy the objectives set by the user, in this case maximizing comfort and minimizing energy use. According to aforementioned literature, an algorithm widely used for energy optimizations of buildings is NSGA-II (non-dominated sorting genetic algorithm). This algorithm is responsible for generating various designs that form different generations. The designs of each generation are evaluated and the optimal designs according to the objectives, have higher chances to pass to the next generation. Additionally, mutations by means of changing variable values occur from one generation to the next, in order to create new designs. For this study the number of generations is set to 78. With a random generator seed set to 1 this means that the number of designs to be generated are 78*25 (from the initial design space)=1950.

**OPTIMIZATION ALGORITHM**

The number of individuals per generation entries in the DOE table are used as the initial population. NSGA-II is a popular algorithm widely used for this purpose as it guarantees the reordering of the design processes until the number of desired design evaluations is reached.
7.3.4 RESULTS FOR OPTIMIZATION WITHOUT ENERGY GENERATION
(1st optimization)

Note that the results illustrated in the following charts refer to the optimization with a constant energy production of approximately 3660 kWh per year for all the designs and glazing ratios. These results are more accurate regarding the influence of the variables on the objectives of minimizing energy and maximizing comfort, since the energy production has an indirect link to the optimization through the window to wall ratio and is not clearly defined as a variable in the charts. In this way, the sensitivity analysis carried out below, has more accurate results.

The post-processing tools offered by mode-FRONTIER are very useful for the visualization of the results and for helping the designer understand the effect of the input variables on the outputs. The visualization through charts also helps the designer to make decisions on which design might be the optimal that satisfies the objectives given.

DESIGNS

The charts 7.73 and 7.74 illustrate how all the various generated designs have scored in terms of energy use and comfort levels. In the second chart, in red dots are the 25 initial designs generated with the uniform latin hypercube method and the green dots are the designs generated by the optimization procedure. As it is illustrated, the optimization process has lead consecutively to designs with lower energy use and higher comfort levels. From these charts, it is obvious that the energy use and comfort levels for a building are conflicting objectives. The designs with higher comfort level have higher energy use and the designs with low energy use tend to have lower comfort levels.

In figure 7.75, one can detect how the latest produced designs (red colour) from the optimization procedure are the ones that satisfy more the objectives initially set. On the contrary, many of the initial designs (blue colour) have higher energy scores and lower comfort levels. This outcome proves that the optimization worked as expected according to the objectives set.
VARIABLE DISTRIBUTION REGARDING THE GOALS OF MINIMIZING ENERGY AND MAXIMIZING COMFORT

WINDOW TO WALL RATIO

The following chart (fig 7.76) illustrates the effect of glazing ratio to the energy consumption and comfort levels of a building. It seems that small windows have a positive effect on reducing energy use, but also increasing comfort levels in a building. This is due the fact that smaller windows lead to reduced solar heat gains and thus reduced cooling loads.

Figure 7.76: glazing ratio effect regarding the objectives

WALL U-VALUE

In figure 7.77, the different wall U values of the walls are scattered on the space without obvious clustering or trends. This indicates that reducing or increasing the wall U values will not drastically improve the energy use or comfort levels on a building that is naturally ventilated in the particular climatic conditions. This might occur due to the fact that in Athens, the outdoor temperatures are for a large part of the year within the indoor temperature range and thus natural ventilation is on for a large period within the year.

Figure 7.77: wall U-value effect regarding the objectives

GLAZING U VALUE

Figure 7.78 illustrates the effect of the glazing U value on the energy use and comfort levels. The glazing U value, similarly to the wall U value shows no clear trends. The different U-values are scattered in the graph. Nevertheless, a weak trend can be detected, of higher U values achieving reduced energy loads and improved comfort. Similarly to the wall U value, this optimization refers to a naturally ventilated building for a large part of the year. This means that the insulating properties of the envelope do not benefit the building so long that the windows are open. Nevertheless, the weak trend for higher glazing U values could be interpreted as the need for the building to have night cooling. The grasshopper model is built with concrete floors that have high thermal mass. This means that the heat accumulates during the day in the concrete mass and is given off at night. But at night when outdoor temperatures fall, natural ventilation might be off and the heat is trapped within the building with closed windows. In this case, opening constructions with a worst performing U value of 1.8 W/m²K might drive the heat outside the building quicker than well insulating constructions. This is a clear indication that night cooling of the building with natural ventilation would be beneficial towards achieving a more sustainable building.

Figure 7.78: glazing U value effect regarding the objectives

SOLAR HEAT GAIN COEFFICIENT

For the solar heat gain coefficient, it is easy to detect the trend of lower values of SHGC tend to reduce the energy usage and improve comfort inside the building. Lower SHGC values mean that the building has less solar heat gains through glazing and therefore lower cooling loads.

Figure 7.79: solar heat gain coefficient effect regarding the objectives
In the chart (fig 7.80) for the effect of infiltration on energy and comfort levels, it is not easy to detect strong tendencies of the different values. Different values seem scattered in the plot without obvious clustering. Since the building is naturally ventilated, changes in the infiltration rate seem to have minimal effect. Nevertheless, low infiltration rates seem to occur to designs with higher comfort levels and lower infiltration rates seem to slightly lower the energy use, looking at the individual set point clusters.

In figure 7.81, the cooling set-point seems to have a drastic effect on the building’s energy use and comfort levels. It is clear that a higher cooling setpoint of 28°C reduces the energy use drastically, but also has a negative effect on comfort levels. On the other hand, a cooling set-point of 24°C improves the comfort levels but highly increases the energy loads. A cooling set point of 26°C seems to have a balancing effect between comfort and energy usage. If the steps for this value were shorter (e.g. 24°C-24.5°C-25°C), then the plot of energy and comfort would form a more defined Pareto front.

The following chart (fig 7.82) shows the effect of glazing ratio on the heating and cooling loads. From this chart one can arrive to the conclusion that smaller windows (30% glazing ratio) lead to reduced cooling loads compared to designs with larger openings. The heating loads are close to zero and thus can not serve as an adequate indication for conclusions.

The following charts (fig 7.83, 7.84) illustrate how the different wall and glazing U-values of the designs lead reduced cooling and heating. For the wall and glazing U values, similarly for energy and comfort, trends on effects on cooling loads and heating loads are not easy to detect. The reason is that in the particular climatic conditions and with mixed mode ventilated building, the insulating properties of the envelope are not active for a large part of the year.
Figure 7.84: glazing U value effect on cooling and heating loads

Figure 7.85: solar heat gain coefficient effect on cooling and heating loads

Figure 7.86: infiltration effect on cooling and heating loads

Figure 7.87: cooling set-point effect on cooling and heating loads

**SOLAR HEAT GAIN COEFFICIENT**

Figure 7.85 shows the effect of SHGC (solar heat gain coefficient) on cooling and heating loads. Lower SHGC values (blue colour) mean that the building has reduced solar gains, thus as it is visible from figure 7.85, this leads to reduced cooling loads and increased heating loads, compared to higher SHGC values.

**INfiltration**

It is evident from the chart (fig 7.86) that low infiltration rates (blue colour) lead to decreased heating loads. High infiltration rates (red colour) produce increasing heating loads. Regarding the cooling loads, no obvious trend can be detected. This happens because it seems to act similarly to natural ventilation and at these climatic conditions, it helps to extract the heating from the building.

**COOLING SET-POINT**

In figure 7.87, the cooling set-point has a clear effect on the cooling loads of the building. Particularly, a cooling set-point of 28 °C induces reduced cooling loads due to the fact that the building is mechanically ventilated for a shorter period of time. On the contrary, a set-point of 24 °C causes increased amounts of cooling loads, since the building needs to be mechanically ventilated for a longer period of time.
VARIABLE DISTRIBUTION REGARDING COOLING AND LIGHTING LOADS

WINDOW TO WALL RATIO

The chart (fig 7.88) that indicates the effect of window to wall ratio on cooling and lighting loads, serves as a manifest indication of how the size of the openings of a building affects the cooling, but predominantly the lighting loads. It is easy to discern that smaller windows mean increased demand for artificial lighting, but on the other hand offer a decrease in the cooling loads.

VISUALIZING THE EFFECT OF VARIABLES ON THE DESIGN

From the parallel coordinates chart, the designer can set various limits regarding the objectives and the values of the variables and see which designs fulfill these restrictions. In figure 7.89, all the designs generated through the optimization process are illustrated. These charts help the decision making process by setting limitations and visualizing the range of designs that fulfill different objective.

The chart in figure 7.90 shows which variables have more influence on the objectives set and which have less influence. Particularly, designs with SHGC (0.3), cooling set-point (26 or lower), glazing U value (1.8 or lower), infiltration rate (0.7 or lower), wall U value (0.3 or lower), window to wall ratio (0.4 or lower) lead to maximized comfort and relatively reduced energy. These range of values for the variables seem to lead to more balanced designs regarding the 2 conflicting objective set in this study. This procedure of setting limits, helps the designer to take decisions on the acceptable value range of the variables.

Figure 7.88: glazing ratio effect on cooling and lighting loads

Figure 7.89: all generated designs and variable combinations

Figure 7.90: setting limits for variables and outputs
SENSITIVITY ANALYSIS

A sensitivity analysis upon the various designs generated is carried out with the aim to understand how the variables influence the objective and which variables are more influential than others.

From correlation chart (fig 7.91) it is visible that the objectives of minimizing energy and maximizing comfort are strongly correlated with the cooling set-point variable. The higher the cooling set-point temperature, the lower the energy use (r=-0.918) and the lower the thermal comfort (r=-0.902). It is obvious that there is a strong correlation between comfort and energy use and weak to moderate correlations for WWR, infiltration and glass U value with energy and comfort. Also, there seems to be a moderate correlation between infiltration and glass U value with cooling set-point. So, apparently the effect these have depends on the cooling set-point temperature.

It is also obvious that the wall U-value has a weak correlation with the objectives, which means that it has minimal influence on minimizing energy use and maximizing comfort. Apart from the general correlation trends visible in this chart, the accuracy of the detailed data of this chart can not be trusted. The reason for this is the optimization procedure that was followed. In order to have an accurate sensitivity analysis, a sampling method should be used by simulating all the 1944 possible combinations of variables. This would allow the best possible quality of sample, that would give the Pearson correlate chart more validity. Nevertheless, if the sample of designs is restricted, modeFRONTIER gives the user the capability to make another type of sensitivity analysis that gives more accurate results. This analysis is made with the sensitivity analysis tool. This analysis is elaborated in the following charts.

Figure 7.91: Pearson correlation chart

Figure 7.92: Effect of variables of minimizing energy use

Figure 7.93: Effect of variables of maximizing comfort

MINIMIZING ENERGY

The chart in figure 7.92 that derives from the sensitivity analysis tool of modeFRONTIER, refers to the effect of the variables on the objective of minimizing the energy use. It is apparent that the cooling set-point has the highest influence on minimizing the energy use, followed by SHGC and window to wall ratio. It seems that glazing U value, infiltration rate and wall U value have minimized influence on this objective. Nevertheless, these results refer only to the selected steps for the variables of this research. If the boundaries for the variables were different, then influence of the variables might be altered. The general ranking of the influence of the variables is expected to remain the same, although the accuracy of the influence values would be slightly altered.

Figure 7.92: effect of variables of minimizing energy use

MAXIMIZING COMFORT

The sensitivity analysis chart (fig 7.93) referring to the objective of maximizing comfort, illustrates an almost similar ranking of the variables, with cooling set-point being the most influential factor for comfort, followed by SHGC and window to wall ratio.

Figure 7.93: effect of variables of maximizing comfort
7.3.5 RESULTS FOR THE OPTIMIZATION INCLUDING ENERGY GENERATION (2nd optimization)

The results illustrated in the following charts refer to the integrated optimization including energy production that is related to the window to wall ratio of the building. The rest of the variable are exactly the same as in the aforementioned optimization.

DESIGNS

The charts in figure 7.94 and 7.95 illustrate how all the various generated designs are ranked in terms of energy use and comfort levels. In the second chart, in red dots are the 25 initial designs generated with the uniform latin hypercube method and the green dots are the designs generated by the optimization procedure. As it is illustrated, the optimization process has lead consecutively to designs with lower energy use and higher comfort levels. From these charts, it is obvious that the energy use and comfort levels for a building are conflicting objectives. The designs with higher comfort level have higher energy use and the designs with low energy use tend to have lower comfort levels.

In the chart (fig 7.96) about the timeline of designs and their effect on energy and comfort, one can detect how the latest produced designs (red colour) from the optimization procedure are the ones that satisfy more the objectives initially set. On the contrary, some of the initial designs (blue colour) have higher energy scores and lower comfort levels. This outcome proves that the optimization worked as expected according to the objectives set, as in the previous optimization without the energy generation optimization.

WINDOW TO WALL RATIO

The chart in figure 7.97 illustrates the effect of glazing ratio on the energy consumption and comfort levels of a building. It seems that small windows have a positive effect on reducing energy use, but also increasing comfort levels in a building.
7.3.6 CHOOSING THE OPTIMAL DESIGN

COMPARISON OF THE 2 OPTIMIZATIONS

The chart in figure 7.98 offers a comparison between the 2 optimizations with the presence and absence of energy production optimization connected to window to wall ratio. As it is illustrated, the comfort levels have remained the same in both cases, but a steeper decline on the energy use is visible on the optimization with the energy production. The reason behind this is the fact that smaller windows that already decrease energy consumption, offer simultaneously larger wall area to be covered with pv panels and thus produce more energy. For the climatic conditions of Athens, with high solar radiation and higher temperatures, it seems that it is beneficial to have smaller windows. In colder climates in northern Europe, the results are not expected to be similar. Window to wall ratio and energy generation are expected to be conflicting with each other, since larger window areas might be needed for lower lighting loads and higher heat gains. This would lead though to reduced energy production.

OPTIMAL DESIGN

The choice of the optimal design relies on the designers priorities either on a design with minimal energy consumption, a design with increased thermal comfort level, or a design that is a compromise for both the above objectives. For this research, the goal is to generate a design that has as much as possible reduced energy consumption, but at the same time is comfortable for more than 80% of the time for the users. As it is obvious in the chart (fig 7.99), it is not possible to achieve both the objectives simultaneously, as they have a conflicting influence on each other.

Subsequently, for this research, a design that has a balancing effect on fulfilling both the objectives simultaneously, is a design with window to wall ratio of 30%, wall U value 0.1 W/m²K, glazing U value 1.8 W/m²K, solar heat gain coefficient 0.3, infiltration rate 0.1 air-changes per hour, cooling set-point of 26 °C (fig 7.100).

Small window size and low solar heat gain coefficient help the building to reduce solar heat gains and thus reduce cooling loads, which are predominant in this climate. A cooling set-point of 26 °C indicates the balance between energy use and comfort levels. Furthermore, the outcome for the rest of the variables is related to the fact that the building is naturally ventilated. As seen in the analysis above, window U value, glazing U value and infiltration rate have minimal effect on the objectives for this thesis. The insulating properties of the envelope remain inactive for a long period since the building is naturally ventilated and the infiltration rate has limited effect in the presence of natural ventilation through the windows. Furthermore, although not included in the calculations for this Thesis, night ventilation and more extensive natural ventilation range seem to lead to reduced energy consumption and higher comfort, as it can be deducted from the outcome of the glazing U-value (1.8). A U value of 1.8 for the glazing means that the heat that is trapped within the building can be transferred to the outdoors more effectively with poor insulating properties of the glazing construction. This indicates that additional natural ventilation and also night cooling through natural ventilation might be beneficial towards a zero energy building in Athens.
7.3.7 CONCLUSIONS

The optimization process has shown that given the boundary conditions for this research, namely a changeover mixed mode ventilated high-rise open plan office building located in Athens, Greece, the shape and orientation of the building have little influence on the energy use intensity. On the contrary, the integrated optimization step of the envelope, HVAC and energy generation systems, has shown that many improvements can be made towards the goal of achieving a high-rise building with reduced energy consumption. From this final step, it seems that the cooling set-point, the window to wall ratio linked to electricity production from PV panels on the building’s facade and natural ventilation together with night-cooling are the key aspects that play an important role on the energy use intensity of the building and its indoor thermal comfort levels.

Finally, the post-processing optimization charts offered in mode-FRONTIER are very helpful in understanding the influence of these variables on the objectives and aid the designer towards making the final decision on a specific design. They also help the design discover a range of permitted values for the variables that would still lead to adequate results. This helps the design link this optimization with other optimizations like structural or financial optimizations. It also serves as a tool for defining strategies and guidelines towards designing high-rise building of reduced energy use and high comfort levels, by defining a range of values and not a restrictive single value for each variable.

**INPUT VARIABLES**

<table>
<thead>
<tr>
<th>DESIGN 1</th>
<th>DESIGN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>wwr: 30%</td>
<td>30%</td>
</tr>
<tr>
<td>wall U value: 0.1 W/m²K</td>
<td>0.1 W/m²K</td>
</tr>
<tr>
<td>glazing U value: 1.8 W/m²K</td>
<td>1.8 W/m²K</td>
</tr>
<tr>
<td>SHGC: 0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>infiltration rate: 0.1 ach</td>
<td>0.1 ach</td>
</tr>
<tr>
<td>cooling set-point: 26 °C</td>
<td>26 °C</td>
</tr>
</tbody>
</table>

**OUTPUTS**

<table>
<thead>
<tr>
<th></th>
<th>DESIGN 1</th>
<th>DESIGN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy use (kWh/m²): 98.99</td>
<td>81.67</td>
<td></td>
</tr>
<tr>
<td>cooling loads (kWh/m²): 33.795</td>
<td>33.795</td>
<td></td>
</tr>
<tr>
<td>heating loads (kWh/m²): 1.061</td>
<td>1.061</td>
<td></td>
</tr>
<tr>
<td>lighting loads (kWh/m²): 11.227</td>
<td>11.227</td>
<td></td>
</tr>
<tr>
<td>comfort (time comfortable during occupancy): 93.2 %</td>
<td>93.2 %</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.100: values of chosen design for the 2 optimizations

7.4 INTEGRATED ENVELOPE AND ENERGY GENERATION MULTI-OBJECTIVE OPTIMIZATION

For this integrated optimization, the window to wall ratio, shading area and pv surface area are optimized. The window to wall ratio can affect the electricity production by PV panels and smaller windows may lead to reduced solar heat gains, but may increase the artificial lighting loads. Additionally, more shading area might lead to reduced cooling loads, but simultaneously increase heating and lighting loads. This optimization, on the contrary to the previous one, is focused on the optimization of the window to wall ratio and shading area for the different orientations of the facades.

Moreover, a multi-objective optimization is implemented. Along with the energy use, the thermal comfort of the occupants plays an important role and is also a prerequisite in the european standards.

For this optimization step as well as in the previous optimization, the energy and daylight simulations will be run with EnergyPlus through Rhino and Grasshopper software via the plug-in Honeybee and the optimization will be driven by modeFRONTIER with the genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm). DesignBuilder cannot currently be connected to this optimization platform, whereas for Grasshopper, a custom node that allows for the coupling of GH and modeFRONTIER, has already been established.

OPTIMIZATION WORKFLOW

[Diagram of optimization workflow showing input files, simulation, optimization program, optimization settings, objective functions, results]
7.4.1 VARIABLES

For this parameter study 2 parameters refer to the building envelope. The parameters are the window to wall ratio for 4 different orientations (North, South, East, West), and shaded area of the openings for 4 different orientations (North, South, East, West). The window to wall ratio and shading area are directly related to the amount of solar heat gains that enter the building due to the openings.

**WINDOW TO WALL RATIO**

For this variable, 5 different values are researched for each of the 4 facade orientations: 20%, 30%, 40%, 50%, 60% glazing ratios. A 20% glazing ratio is expected to reduce cooling loads, but increase electricity loads, whereas a 60% glazing ratio is expected to increase cooling loads and decrease electricity loads since it refers to almost a fully glazed facade that allows more daylight in the building. The glazing ratio varies for the different facade orientations.

**SHADING AREA**

For this variable, 4 different values are researched for each of the 4 facade orientations: 25%, 40%, 55%, 70% shaded area of the openings. 25% shaded glazed area is expected to increase cooling loads, but reduce electricity loads, compared to 70% shaded glazed area that is expected to decrease cooling loads and increase electricity loads. The area of the shadings varies for the different facade orientations.

**ENERGY GENERATION FROM PHOTOVOLTAIC PANELS**

This optimization variable is inextricably linked to the window to wall ratio of the building. It refers to PV panels mounted vertically on all 4 facades of the building. It is obvious that for lower glazing ratios of 20%, higher amounts of electricity will be generated and reversely, for high glazing ratios of 50% and 60%, the least amount of electricity will be produced. Nevertheless, for glazing ratios of 20%, the daylight that infiltrates the building will be diminished compared to a 60% glazing ratio.
HVAC SYSTEMS

COOLING SET-POINT
The cooling set point in this optimization is set to 26°C and refers to the indoor temperature above which the mechanical ventilation system will start working. The value of 26°C allows for a widening the time span of natural ventilation (21°C – 25°C of indoor temperature) compared to the previous optimization, that only allowed natural ventilation from 21°C to 23°C (indoor temperature). This change is expected to further reduce the energy loads of the building.

WALL U-VALUE
For the external wall U-value of the building a construction with 0.1 W/m²K is used that refers to well insulated buildings. The current national standards of Greece that allow a value of 0.5 W/m²K for this climatic zone. Since the building is naturally ventilated, the protection of the insulation is restrained only for the hours when the windows are closed.

GLAZING/FRAME U-VALUE
This U-value refers to the glazing and frame construction of the openings. For the openings’ U-value of the building 1.8 W/m²K is used, which refers to a double glazing with not good performance. Nevertheless, the 1.8 value is lower than the current national standards of Greece that allow a value of 2 W/m²K for glass facade. The building simulated is naturally ventilated and the insulation of the openings is only useful for the time-span that the windows are closed. Additionally, this U value means that the building can extract the accumulated heat trapped within the building when the windows are closed, quicker to the outside compared to a construction with lower U value.

GLAZING G-VALUE
For the G-value or solar heat gain coefficient the 0.3 value that is used, allows the least amount of solar heat gains in the building. For the climatic conditions of Athens, with intense solar radiation, smaller solar heat gains are expected to reduce the cooling loads and thus reduce the total energy demand of the building.

AIR-TIGHTNESS
Air-tightness of the facade, or infiltration, allows for heat transfer between indoors and outdoors through the envelope. The rate of the infiltration is set to 0.1 air changes per hour. Since the building simulated is already naturally ventilated, the amount of influence of the air-tightness is not important as shown in the previous optimization.

RESULTS-OUTPUTS

For this optimization the adaptive thermal comfort is changed to the European Standard EN-15251, whereas in the previous optimization the ASHRAE 55 standard is used. This component is set to compute the prevailing outdoor temperature from a weighted running mean of the last week. The building is also calculated at comfort class 3, which refers to a building with 80% of the occupants comfortable. As seen from the results, the difference between the previous default setting and these settings are not bringing any significant change to the results.

Figure 7.102: adaptive comfort, model settings
MODEL INPUT

The following input data are used to run the simulations and are based on the current national standards of Greece for the design and construction of office buildings and the results derived from the aforementioned optimizations. The simulations are made for an annual period from January 1st until December 31st.

SIMULATION SETTINGS
- time steps per hour: 6

ACTIVITY
- occupancy density: 0.1 persons/m²
- computers load: 15 W/m²
- heating set-point: 20 °C
- heating set-back: 15 °C
- cooling set-point: 26 °C
- cooling set-back: 30 °C
- minimum fresh air: 8.333 l/s-person=30 m³/h/person

CONSTRUCTION
- air-tightness: 0.1 ach
- external wall U-value: 0.1 W/m²K
- floor U-value: 0.472 W/m²K
- floor construction: acoustic tile/50mm insulation board/200mm heavyweight concrete
- internal partition U-value: 2.58 W/m²K
- internal partition construction: 19mm gypsum/wall air space resistance/19mm gypsum

OPENINGS
- SWS: (variable)
- shaded area (% of glazed area): (variable)
- SHGC: 0.3
- U-Value: 1.8 W/m²K

LIGHTING
- normalized power density: 3.2 W/m²·100lux
- lighting control: occupancy schedule

HVAC
- natural ventilation: on
- min indoor temp for nv: 21 °C
- max indoor temp for nv: 25 °C
- mechanical ventilation: on
- heat recovery: on
- system: ideal loads

PV
- efficiency: 12%

7.4.3 OPTIMIZATION WITH modeFRONTIER

WORKFLOW

The optimization was implemented with modeFRONTIER 2016 update1 version. The number of evaluated designs is 1000. The time needed for the evaluation was 44h and 24min. The evaluation time of 1 design was approximately 2' 40''. The optimization run on an i7-5820K, CPU at 3.3 GHz.

The workflow of the optimization as visualized in the interface of modeFRONTIER consists of the inputs, the outputs, the connection to Grasshopper, the Design of Experiments component and the optimization algorithm component. Additionally, objectives need to be set in order for the optimization procedure to be applied according to an objective. The objectives for this optimization are minimizing energy and maximizing comfort.

Figure 7.103: workflow in modeFRONTIER interface

VARIABLES AND STEPS

The user needs to manually apply the variables' lower and upper boundaries and the number of intermediate steps between the boundaries (fig 7.104).
DESIGN OF EXPERIMENTS (DOE)

The design of experiments component contains various space filler methods. As in the previous optimization, Uniform Latin Hypercube is used to generate a number of designs with randomly assigned variables. For this optimization, 25 designs were generated as a starting point.

OPTIMIZATION ALGORITHM

The optimization algorithm drives the optimization towards creating designs that satisfy the objectives set by the user, in this case maximizing comfort and minimizing energy use. As in the previous optimization, the NSGA-II (non-dominated sorting genetic algorithm) is used. This algorithm is responsible for generating various designs that form different generations. For this study the number of generations is set to 78. With a random generator seed set to 1 this means that the number of designs to be generated are 78*25 (from the initial design space)=1950.

7.4.4 RESULTS FOR OPTIMIZATION WITH ENERGY GENERATION

The results illustrated in the following charts refer to the optimization including energy production (electricity). The energy production is linked to the different glazing ratios of the different facade orientations. Thus, the sensitivity analysis carried out below, shows the augmented influence of window to wall ratio due to the energy

DESIGNS

The visualization through the following charts helps the designer understand the influence of passive design and active measures, since they are optimized in an integrated procedure.

The chart (fig 7.105) illustrates how all the various generated designs are ranked in terms of energy use and comfort levels. The red dots are the 25 initial designs generated with the uniform latin hypercube method and the green dots are the designs generated by the optimization procedure. The optimization process has lead consecutively to designs with lower energy use and higher comfort levels. It is evident from the chart, that the energy use and comfort levels for a building are conflicting objectives.

In figure 7.106, the latest simulated designs (red colour) from the optimization procedure are the ones that satisfy more the objectives initially set.
VARIABLE DISTRIBUTION REGARDING THE GOALS OF MINIMIZING ENERGY AND MAXIMIZING COMFORT

EAST WINDOW TO WALL RATIO

The following chart (fig 7.107) illustrates the effect of glazing ratio of the east facade on the energy consumption and comfort levels of a building. It seems that small windows (20% glazed area) have a positive effect on reducing energy use and increasing comfort levels. Smaller windows lead to reduced solar heat gains and thus reduced cooling loads. Additionally, the effect of small windows is aided towards minimizing energy with the increased energy production from pv panels.

WEST WINDOW TO WALL RATIO

Also for the west and north orientation it seems that small windows have a positive effect on reducing energy use, and increasing comfort levels in a building, as illustrated in the charts 7.108 and 7.109.

SOUTH WINDOW TO WALL RATIO

The following chart (fig 7.110) illustrates the effect of glazing ratio of the south facade on the energy consumption and comfort levels of a building. It seems that small windows have a positive effect on reducing energy use. Nevertheless, smaller windows don’t lead to designs with increased thermal comfort for the south part of the building. Smaller windows lead to reduced solar heat gains and thus reduced cooling loads. The clear distinction between the different glazing ratios regarding the energy use is influenced by the energy production, since the south facade is the longest facade of the building and receives the largest amount of solar radiation, due to its orientation.

Only for the south facade, larger windows (60% wwr) seem to lead to marginally improved comfort levels than smaller windows (20% wwr). That could be attributed to the fact that from the south, solar radiation enters the building almost vertically and does not reach the interior of the floor plan, so the area of the openings is not so important for the solar heat gains. Furthermore, bigger windows mean more opening area for natural ventilation and thus the indoor thermal comfort levels might be increased.
SHADING

Less shading area of 25% of the glazed area (blue colour) means that the building allows more daylight in the building and thus lead to reduced lighting loads. For the south orientation it seems that shading area of 25% of the glazed area is marginally better for the energy use and thermal comfort levels of the building (fig 7.114). For the other orientations, the optimization of the shading area seems to have much less influence on the objectives of the optimization and that is visible from the fact that the coloured dots are scattered with no clear trend on the charts (fig 7.111, 7.112, 7.113).

Since in this optimization, the visual comfort inside the open plan office area is not taken into account, the conclusions derived from this optimization are not conclusive for the final design of a building shading. Nevertheless, it is obvious from the results, that good exploitation of the daylight is substantial towards the reduction of energy use.

Additionally, it is evident that for a building in the hot and dry climate of Athens, it is preferable to have a facade with smaller windows and less shading area at the openings, than bigger openings with more shading area. This means that the wall construction is better performing at preventing heat gains entering the building than the material of the shading system.

CONCLUSIONS

As a conclusion for the window to wall ratio optimization, it seems that any potential differentiation of the window to wall ratio per facade orientation is overshadowed by the influence of energy production on the facade. This means that the effect of electricity production is more influential than any energy saving from the sum effect of window to wall ratio per orientation to the buildings cooling, heating and lighting loads. This is the case for the climatic conditions of Athens with large amounts of solar radiation and clear sky for a large part of the year. For northern Europe the results may differ and the differentiation of window to wall ratio per facade, may have more influence.

The amount of shaded area has minimal influence on the total energy use of the building, especially for designs with smaller windows, though good daylight exploitation with efficient shading control leads to reduced energy consumption.

Nevertheless, these results indicate clearly the need for implementing the integrated methodology with passive and active measures, rather that applying the stepped strategies. It is evident from this research, that some conflicting issues such as the area of pv panels vs the amount of glazed area need the integrated methodology in order for the designer to establish the balancing point.
VARIABLE DISTRIBUTION REGARDING COOLING AND HEATING LOADS

WINDOW TO WALL RATIO

The chart (fig 7.118) shows the effect of glazing ratio of the south facade on the heating and cooling loads. From this chart one can arrive to the conclusion that smaller windows (20% glazing ratio) lead to reduced cooling loads compared to designs with larger openings. Since the south facade is more exposed to solar radiation, it is expected that smaller windows would lead to reduced cooling loads.

For the rest of the facade orientations, it seems evident that the cooling loads are not substantially influenced by the window to wall ratio. On the contrary, the heating loads seem more influenced by the window area. Particularly, small windows seem to lead to reduced heating loads, especially for the north facade, which is less affected by the energy production due to lower solar radiation. This can be attributed to the face that smaller windows mean more wall area with better insulating properties than the glazing construction. Nevertheless, the heating loads are almost minimal compared to the total energy use, so they play a minimal role to the building design and construction optimization.
**SHADING**

Figures 7.119, 7.120, 7.121 and 7.122 show the effect of shading per facade orientation on the cooling and heating loads. Less shading (25% of the glazed area) (blue colour) does not show any clear influence on the cooling and heating loads, with the exception of the shading of the south facade, where less shading seems to lead to marginally reduced heating loads, by increasing solar gains. Nevertheless, the heating loads are minimal for the climate in research.

**VARIABLE DISTRIBUTION REGARDING COOLING AND LIGHTING LOADS**

**WINDOW TO WALL RATIO**

For the east and west orientation (fig 7.123, 7.124), smaller windows (20% wwr) lead to reduced cooling loads, but do not substantially affect the lighting loads.

For the north orientation (fig 7.125), smaller windows (20% wwr) seem to lead to increased lighting loads, due to worse exploitation of the daylight compared to larger windows (60% wwr). The effect of the window to wall ratio on the cooling loads is minimal.

Regarding the south orientation (fig 7.126), it is clear how the window to wall ratio affects the cooling loads of the building, but the effect on the lighting loads is minimal since the solar radiation enters the building in a steep incidence angle and thus does not reach at the greatest depth of the floor plan.

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**Figure 7.119**: Shading effect of east facade on cooling and heating loads

**Figure 7.120**: Shading effect of west facade on cooling and heating loads

**Figure 7.121**: Shading effect of north facade on cooling and heating loads

**Figure 7.122**: Shading effect of south facade on cooling and heating loads

**Figure 7.123**: Glazing ratio effect of east facade on cooling and lighting loads

**Figure 7.124**: Glazing ratio effect of west facade on cooling and lighting loads

**Figure 7.125**: Glazing ratio effect of north facade on cooling and lighting loads

**Figure 7.126**: Glazing ratio effect of south facade on cooling and lighting loads
SHADING

Figures 7.127, 7.128, 7.129 and 7.130 show the effect of shading per facade orientation on the cooling and lighting loads.

For the east and west orientation, shading area seem to have minimal effect on the cooling and lighting loads of the building. For the south and north orientation, shading optimization is more powerful and it seems that less shading area (25% of the glazed area) leads to reduced lighting loads, but has minimal effect on the cooling loads.
A sensitivity analysis upon the various designs generated is carried out, in order to understand how the variables influence the objective and which variables are more influential than others.

From correlation chart (fig 7.131) it is visible that the objective of minimizing energy is correlated with the south window to wall ratio with a positive correlation ($r=0.769$). The south facade receives higher solar heat gain loads since it’s the longest facade of the building exposed to the south. It seems that smaller windows have a great influence on minimizing cooling loads and also producing more energy through pv panels.

The objective of maximizing comfort is strongly correlated with the north window to wall ratio with a negative correlation ($r=-0.791$). As the window to wall ratio is reduced, the comfort levels are increased. Since, in the north orientation, the solar radiation is more indirect, and this facade has less solar heat gains, it seems that more wall area helps the north area of the building to maintain the indoor comfort levels through more insulation. Furthermore, the effect of energy production seems also not to have such a big impact compared to the other orientation, since the amount of direct solar radiation is minimal.

Apart from the general correlation trends visible in this chart (fig 7.131), the accuracy of the detailed data of this chart could have more validity. The reason for this is the optimization procedure. In order to have an accurate sensitivity analysis, a sampling method should be used. This would allow the best possible quality of sample, that would give the Pearson correlation chart validity. Nevertheless, if the sample of designs is restricted, modeFRONTIER gives the user the capability to make another type of sensitivity analysis that gives more accurate results. This analysis is made with the sensitivity analysis tool as elaborated in the following charts.

The chart in figure 7.132 that derives from the sensitivity analysis tool of modeFRONTIER, refers to the effect of the variables on the objective of minimizing the energy use. It is apparent that the window to wall ratio of all the facade orientations are more influential than the shading area optimization. The most influential variable is the south facade window to wall ratio, as shown also in the Pearson correlation chart. The general ranking of the influence is affected by the lack of a good quality sample with more designs.

The sensitivity analysis chart (fig 7.133) referring to the objective of maximizing comfort, shows that the most influential variables are referring to the window to wall ratio, but here also the south facade shading area has a relatively important role. The most influential variable though is the window to wall ratio of the north facade as shown also in the Pearson correlation chart. Also here the accuracy of the ranking is rather compromised by the lack of a good quality sample with more designs.
7.4.5 CHOOSING THE OPTIMAL DESIGN

OPTIMAL DESIGN

The choice of the optimal design relies on the designers priorities either on a design with minimal energy consumption, a design with increased thermal comfort level, or a design that is a compromise for both the above objectives. For this research, the goal is to generate a design that has as much as possible reduced energy consumption, but at the same time to retain high comfort levels. As seen in the chart (fig 7.134), it is not possible to achieve both the objectives simultaneously, as they have a conflicting influence on each other. Nevertheless, it is visible from the chart that the designs located at the Pareto front have a range of comfort level from 96.49% to 97%, which is a minimal difference. So from this Pareto front it is possible to chose the design with the smallest amount of energy loads.

The design chosen fulfills both the objectives simultaneously, and is a design with window to wall ratio of 20% (for all the facade orientations), wall U value 0.1 W/m²K, glazing U value 1.8 W/m²K, solar heat gain coefficient 0.3, infiltration rate 0.1 air-changes per hour, cooling set-point of 26 °C and shading area at 25% of the glazed area (for all the facade orientations).

Small window size helps the building to reduce solar heat gains and thus reduce cooling loads, which are predominant in this climate. Additionally, low shaded area leads to better exploitation of the daylight.

From the chart of energy end uses and energy production (fig 7.136) it is obvious that equipment and cooling loads are the cause of increased total energy loads, followed by lighting loads. Moreover, energy production seems to have a large impact on reducing energy loads. In this research the equipment loads were calculated with 15 W/m², which is the maximum allowed by the current Greek regulations.

**OUTPUTS**

- energy use (kWh/m²):
  - 73.13
- cooling loads (kWh/m²):
  - 29.50
- heating loads (kWh/m²):
  - 0.96
- lighting loads (kWh/m²):
  - 10.54
- comfort (time comfortable during occupancy):
  - 96.49 %
CONCLUSIONS

The final integrated optimization of the envelope and energy generation systems, has shown that it is very important to combine in an integrated methodology the optimization of passive and active systems. The results of this optimization show that the window to wall ratio potential variation per facade orientation is overshadowed by the effect of energy generation on the opaque elements of the facade. This shows that for the specific climatic conditions of Athens, there is no need for adaptive window to wall ratio design per facade orientation in the presence of energy generation on the facades. For other climatic conditions though, like for countries of northern Europe, the results might differ, and the effect of adaptive design per orientation could be stronger.

Furthermore, the results show that it is more energy efficient for a building in the climatic conditions of Athens to have smaller windows and less shading area, rather than bigger windows and more shading area. This can be attributed to the fact that the wall construction is better at protecting the building from heat gains and solar heat gains from the outdoor than the material of the shading devices. For the shading area optimization, the results show that the effect of the shading area is minimal towards the energy loads of the building, in the presence of a window to wall ratio of 20%. On the contrary, since the indoor floor plan is already shaded by the existence of small windows (20% wwr) then the small shading area of 25% of the total glazed area leads to better exploitation of the daylight. This means that the designers in Athens should focus on designing building with smaller openings, rather than trying to optimize the shading devices of buildings with larger openings.

Thus this integrated methodology of both the shading area and the window to wall ratio, shows that instead of optimizing the shading area per facade orientation in a stepped methodology, integrating it in the optimization of other variables like window to wall ratio shows that there is no need for shading area optimization per orientation and instead, the effect of smaller windows overshadows the shading optimization effect and leads to better results.

Additional, the final energy use sources diagram shows that investing to more energy saving equipment is of great importance towards the aim of achieving a nearly zero-energy high-rise office building.

Finally, improving the natural ventilation temperature range (21°C-25°C) from the previous optimization (21°C-23°C) has evidently lead to reduced energy loads. Thus improving the effect of natural ventilation is of paramount importance for a high-rise open plan office building in the climatic conditions of Athens or other areas with hot and dry but relatively temperate climate.
The guidelines could help a designer that aims to design a building with reduced energy loads and high comfort levels in similar climatic conditions as in Athens, Greece. By incorporating the results of the optimization study and the sensitivity analysis of the different variables into the guidelines, a designer can design a building with reduced energy loads without performing an optimization. Although the guidelines offer a more generalized strategy that could be applied to many buildings, large and complex projects, especially those located in a dense urban environment, may be more benefited by applying the optimization methodology on the design of the particular building and thus generating better performing designs. Moreover, the optimization methodology could also be used for buildings located in different climatic zones, but this would lead to altered guidelines.

The guidelines indicate a range of values that different construction and design values can have and this leads to a range of energy efficient designs with high comfort levels. Having a wider range of values offers the designer a freedom to customize the architectural design, as comfort and energy efficiency are only a few of the parameters that lead to the final design of a building. Some variables have a more restricted range of values and other can fluctuate more within a wider spectrum of values, depending on their influence on the energy use and thermal comfort levels of the building.
LAYOUT

In the climatic conditions of Athens with hot and dry summers and high solar radiation, solar heat gains are the main cause of increasing cooling loads. A more slender building is translated to more facade surfaces compared to the volume of the building. On the contrary, a more compact building has less facade surface than a slender building of the same volume and height. More facade surface allows increased solar heat gains in the building and thus the building demands more cooling loads. Therefore, for the climatic conditions of Athens, a more compact layout is preferable for reducing the predominant source of energy consumption, which is cooling.

Nevertheless, the designer should not be restricted towards a more compact building, since the gains in energy consumption compared to that of a slender building, would be minimal.

Regarding the lighting loads, the design is advised to design a building with less facade area towards the south and north orientation, since the solar radiation falls more vertically on the facade, but this is independent of the layout shape.

ORIENTATION

The optimal orientation for a more slender building layout is linked to the amount of solar heat gains in the building and the occupancy schedule of the building. In order to achieve reduction of the total energy demand, the designer is advised to orientate the longest facade towards the south. This is beneficial to the building, since solar radiation falls vertically on the south facade and does not reach the deepest length of the layout. This leads to reduced cooling loads. Additionally, the office occupancy schedule also favours the same orientation of the layout.

The designer though may feel free to use various orientations, since the optimal orientation does not induce considerable energy reduction.

WINDOW TO WALL RATIO

For the climatic conditions of Athens, Greece or similar, a designer is strongly advised to create a building with small glazed surfaces. This is in benefit not only of the energy reduction, by also of the energy generation of the building. Regarding the energy production, more wall surface area means that the building is capable of producing more on-site electricity by applying photovoltaic panels on the walls. Furthermore, referring to the energy reduction aspect, solar heat gains and subsequently cooling loads are reduced as the amount of glazing is reduced (fig 8.3, 8.4). Moreover, the comfort levels of a building with smaller window area are higher than that of a building with larger windows. The only drawback of having smaller windows is that the amount of artificial lighting is increased (fig 8.3).

If the design aims to create a building that included energy generation from PV panels mounted of the walls of the building, then the designer is strongly advised to use small openings of 20% glazing to wall area. If energy generation on the facades of the highrise building will not be implemented, then the designer could as well as not be highly restricted by the window opening and could also apply more shading surfaces on the building while maintaining larger openings. Nevertheless, high window to wall ratios of 60%, 70% and 80% are not advisable for the climatic conditions of Athens, Greece.

The designer is also rather free to differentiate the glazed area per facade orientation preferably ranging from 20% to 40% window to wall ratio.
SHADING

Additionally, the designer having applied smaller window to wall ratio on the building design, would be free to apply varying shading systems, with differentiated shading areas per facade orientation. Nevertheless, since small openings protect the building from excessive solar gains and solar radiation, the amount of shading should be minimal, in order to exploit daylight. The designer should then focus more on designing a shading system that leads to increased visual comfort.

GLAZING G-VALUE

The glazing G-value is an important factor the designer needs to take into account when designing a high-rise building in Athens. In order to reduce solar heat gains and thus cooling loads, the design is strongly advised to use glazing with low G-value of 0.3 (fig 8.6). A value of 0.3 means that only a small fraction of solar radiation penetrates through the glazing.

While applying low G value glazing is crucial for the energy reduction and comfort increase of the building, the designer could also consider using more shading surfaces that have the same effect of blocking solar heat gains from infiltrating the building.

COOLING SET-POINT

The most influential factor towards designing a less energy consuming building in the climate of Athens is the cooling set-point. A cooling set-point of 28 °C leads to considerable energy reduction compared to a cooling set-point of 24 °C. Nevertheless, for setting the cooling set-point of the mechanical ventilation system, the designer needs to take into account also the thermal comfort levels of the building. In order to achieve a building that is more than 80% comfortable annually, the designer should use a cooling set-point of 26 °C or lower (fig 8.7).
INFLUENCE ON VARIABLES ON THE ENERGY USE OF THE BUILDING

RELATED TO RESULTS OF THE FIRST OPTIMIZATION ROUND

Apart from the influence of the values of the different values on the energy loads of a building, it would be useful for a designer to know the amount of influence of the different variables on the energy and thermal comfort levels of the building. This would help the designer to prioritize the measures taken for a more sustainable high rise building.

Regarding the influence of the envelope and HVAC variables on energy use, it is evident that the cooling set-point is the most important factor that could lead to a building of lower energy use. The cooling set-point is related to the thermal comfort levels of the building, henceforth the designer must be aware that it may not be viable to compromise the level of comfort of the building to benefit energy savings.

With regard to the envelope variables, the designer must take into account that the glazing G value and the window to wall ratio has more potential and room for improvement. Both of the variables are related to decreasing the solar heat gains in the building and thus reduce cooling loads.

The rest of the variables, namely the glazing U value, infiltration and wall U value have little influence towards the path of a zero energy building under the conditions of a naturally ventilated (mixed mode) building in the climatic conditions of Athens.

Figure 8.8: influence of variables of first optimization round regarding their energy use

RELATED TO RESULTS OF THE SECOND OPTIMIZATION ROUND

Regarding the adaptive facade design per orientation, the designer should focus on first implementing the appropriate window to wall ratios on the envelope, especially in the south, east and west facades. For the north window to wall ratio and for the shading area of all the orientations, the designer is more free to design the building without many restrictions from the energy perspective.

Figure 8.9: influence of variables of second optimization round on energy use
INFLUENCE ON VARIABLES ON THE THERMAL COMFORT OF THE BUILDING

RELATED TO RESULTS OF THE FIRST OPTIMIZATION ROUND

The influence of the aforementioned variables on thermal comfort has substantially little difference to the ranking of those on the energy use of the building. In this respect, cooling set point is the most crucial factor of increasing thermal comfort levels, but the designer must be aware that a cooling set-point that leads to increased thermal comfort leads at the same time great in great increase of energy use and thus the designer may be restricted towards radical changes of this variable.

The glazing G value and window to wall ratio have relative potential towards increasing thermal comfort as well as decreasing energy use. This means that the designer should focus on reducing the solar heat gains of the building in order to have a sustainable and comfortable building.

Infiltration, glazing U value and wall U value have the a miniscule influence on thermal comfort as well as the energy use of the building, since the building is naturally ventilated for a large period annually and thus the insulating properties of the envelopes are not active for this time span.

As a conclusion, the strategy towards a zero energy high-rise open office building in Athens, Greece shows that decreasing solar heat gains and adjusting the cooling set point of the mechanical ventilation system of the building are the key aspects of an energy efficient design.

INFLUENCE OF VARIABLES ON THERMAL COMFORT

COOLING SETPOINT

GLAZING G-value

WWR

INfiltration

GLAZING U-value

WALL U-value

Figure 8.10: influence of variables of first optimization round on thermal comfort

RELATED TO RESULTS OF THE SECOND OPTIMIZATION ROUND

Regarding the adaptive facade design per orientation and its connection to thermal comfort levels, the designer should focus on first implementing the appropriate window to wall ratios on the envelope, especially in the north, east and west facades. For the south window to wall ratio and for the shading area of all the orientations, the designer is more free to design the building with less design restrictions from the energy perspective.

Figure 8.11: influence of variables of second optimization round on thermal comfort
To conclude, a summary of the above analysis of the guidelines could be the boundaries for the different design variables that can be compared to those of the current Greek regulation.

The cooling set point lower boundary is 26 °C, similar to that of the Greek regulation, a value that balances the need for high thermal comfort and low energy use.

The glazing G value is advisable to be set at the low value of 0.3 for the climatic conditions of Athens, that helps reduce the solar heat gains.

The window to wall ratio is advisable to have an upper limit of 40% (glazing). With higher window to wall ratios, the designer should be aware of the great compromises at the expense of both energy use and indoor thermal comfort levels that will occur.

The upper boundary for the wall U-value should preferably be 0.3 W/m²K. Although as seen from this research, the influence of the wall U value is not so important as other variables, nevertheless, for the north orientation, the wall U value could have a higher influence. For this research, the highest value given to the variable of wall U value is the value 0.3 W/m²K, but potentially, higher values might also be acceptable. The value of 0.3 is also close to the value given by the current Greek regulation (0.5 W/m²K). The designer should be aware that investing in construction with better performing wall U values of 0.1 W/m²K will not necessarily improve the energy use performance of a building. That might not be the case though for different climatic conditions.

The lower boundary of the glazing U value is proposed to be 0.6 W/m²K, which is also the lowest value given to the variable of the glazing U value in this research. A U value of 0.6 W/m²K refers to a construction with high insulating properties. This research has shown that a higher value of 1.8 W/m²K is also acceptable for the design of a building in Athens. This conclusion is in line with the limit for the glazing U value of the current Greek regulation (2 W/m²K). The designer should be aware of the in these climatic conditions, investing in glazing constructions of very low U value will not lead to a better performing building and thus might be proved cost-inefficient.

Finally, for the envelope air-tightness, the designer should be aware that since the building should be naturally ventilated through a large part of the year, investing in an envelope construction with very low infiltration rates would not lead to significant improvements of the energy use levels and thermal comfort of the building. Thus a value of 0.5 air change per hour could be advisable as an upper limit for new constructions in Athens, Greece.

<table>
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<td>-</td>
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<td>40%</td>
<td>-</td>
</tr>
<tr>
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<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>glazing U value (W/m²K)</td>
<td>0.6</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>infiltration (ach)</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 8.12: value range of variables as a result of the optimizations in this research
09

DESIGNS
1st OPTIMIZATION (PARETO FRONT DESIGNS)

minimize energy (kWh/sqm) vs. maximize comfort (%)

- **Design 1**
  - Wall U value: 0.1 W/m²K
  - Glazing U value: 0.6 W/m²K
  - Glazing G value: 0.3
  - Infiltration: 0.1 ach
  - Cooling set point: 24 °C

- **Design 2**
  - Wall U value: 0.1 W/m²K
  - Glazing U value: 1.8 W/m²K
  - Glazing G value: 0.3
  - Infiltration: 0.1 ach
  - Cooling set point: 26 °C

- **Design 3**
  - Wall U value: 0.1 W/m²K
  - Glazing U value: 1.8 W/m²K
  - Glazing G value: 0.3
  - Infiltration: 0.1 ach
  - Cooling set point: 28 °C

Window to wall ratio: 30%
OPTIMAL DESIGNS WITH UNIFORM WINDOW TO WALL RATIO (PER ORIENTATION)

20% WWR

30% WWR

40% WWR

OPTIMAL DESIGNS WITH ADAPTIVE WINDOW TO WALL RATIO (PER ORIENTATION)

20%-30% WWR

20%-40% WWR
OPTIMAL DESIGN WITH LOWEST ENERGY USE (20% window to wall ratio)
DESIGN RANGE OF LOWEST ENERGY-HIGH COMFORT RESULTS (SHAPE AND ENVELOPE VARIABLES)
LIMITATIONS

The transition from the literature research to the experimental phase of the thesis was marked with several restrictions.

For the shape and orientation optimization in Design Builder, 4 different shapes were evaluated with a transition from a more elongated shape, to a more compact one. The transition between shapes was not realized with more dimensionally dense consecutive steps, since realistic floor plan depths and core sizes served as a limitation.

The envelope, HVAC and energy production optimization was implemented in Grasshopper via the Honeybee plug-in. This software restricts the optimization on HVAC systems and due to long calculation times, simplifications needed to be made in the building model and in the number of design and construction variables.

Moreover, due to time restrictions, the accuracy of the simulations was compromised, although within the scale of this research the final outcome might not have been altered.

Additionally, more in depth knowledge on setting the appropriate optimization algorithms in modeFRONTIER could potentially lead to reduced time spent on the optimization procedure.

The number of different designs generated from the coupling of Grasshopper and modeFRONTIER was restricted by limitations in the connection between the 2 software.

Discrepancies between the results of Grasshopper and Design Builder are mainly attributed to the limited possibilities in the settings of the former software, but these do not seem to alter the final result of this research.
CONCLUSIONS FROM RESEARCH

The review on environmental problems related to buildings and precedent analysis of low-energy high-rise office buildings built in temperate climates helped to define the strategies towards optimizing elements of the building that can potentially have high influence in energy consumption. The review showed the limitations of passive and active strategies towards creating a nearly zero-energy building. These limitations are reflected also in the built precedents and indicate the difficulties of designing a zero-energy high-rise building.

Through the literature review, it is evident that legislation and regulations towards zero-energy buildings do not yet guarantee the design of nearly-zero energy buildings, especially referring to the national standards of Greece.

The review on previous optimization studies of energy performance optimization of buildings served as a reference for the settings and limits of the optimization processes that can be realized within a restricted time span and within the scope of a master thesis in an academic environment.

Establishing guidelines for the design of a high-rise office building derive from the results of the optimization process. Nevertheless, due to simplifications made in order to drastically reduce the energy and daylight simulation time, more time and computing power would be needed in order to achieve more accurate results for high-rise buildings that could include potential surroundings of the building.

From the literature stage of this thesis it became apparent that building energy performance optimization is not enough to achieve a nearly zero energy high-rise office building according to the European standards. Apart from optimizing certain design and construction parameters of a building, reducing the energy consumption in a building while maintaining a high comfort level in this climate, would mean better exploitation of natural ventilation, more energy generation from on and off-site generation systems, further optimization of the facade elements according to orientation and location on the building and use of adaptive systems for shading or cooling that could be sensitive to the environmental change. Nevertheless, through the optimization it became apparent which building elements have the highest influence in the building’s energy consumption and this could serve as information for further research on improving these aspects. More specifically, a designer in Athens, Greece should consider employing and improving the following aspects of their building design: the cooling set-point, the window to wall ratio linked to electricity production from PV panels on the building’s facade and natural ventilation together with night-cooling.

The optimization methodology implemented in this Thesis, that allows for integrated optimization of several design and construction variables and testing of a large number of different designs, has proven to bring about results that may not have derived from other stepped strategies. This is because several design and construction variables have conflicting results on various energy loads like heating, cooling and lighting. For example larger window might lead to reduced artificial lighting, but increased cooling loads and decreased energy production from the facades. Especially on northern countries with colder climates and less solar radiation, the conflicting effect might be more noticeable. Moreover, the integrated process makes it easy for the designer to detect conflicting design and construction variables in many climatic conditions and find the right trade-off point between them.

Additionally, the integrated methodology has shown from the results of this research, that for the climatic conditions of Athens, adaptive design of the facade openings per orientation and adaptive shading area per orientation will not lead to reduced energy loads in the presence of smaller openings and energy production systems in the facade. The presence of active systems has overshadowed the aforementioned passive design optimization. Also, the integrated optimization of window to wall ratio and shading area has overshadowed the effects of adaptive shading area per orientation. This result proves the real benefit of this integrated methodology compared to the existing stepped strategies such as the Trias Energetica or the New Stepped Strategy. It is manifest that the integrated strategy by means of integrating multiple variables for both passive and active systems and establishing the balancing point between them is the future towards the strive for nearly zero-energy buildings and performs better for buildings where on-site energy production on the facades is important, such as high-rise buildings, in climates with high solar radiation levels.

Moreover, this multi-objective optimization between energy use and thermal comfort makes it clear that those 2 objectives are substantially contradicting. More often than not, a building with greatly reduced energy need is not a comfortable building and the opposite. Thus, thermal comfort and also the current thermal comfort standards as proven in this Thesis are a hindrance towards a zero energy building.

All the above lead to the conclusion that the definition of the European Union for nearly-zero-energy building that entails energy production within the site of the building may be difficult to be implemented. The implementation of this definition would be particularly difficult to implement especially on high-rise buildings within the dense urban environment with potentially many surrounding high-rise buildings. The energy production within such an urban environment from the facades of high-rises would be hindered by overshadowing between buildings and roof surface compared to volume is limited for high-rises. Furthermore, it might prove a non viable option to massively employ cost-inefficient design methods like atria, or expensive energy producing systems with higher efficiencies in the majority of the building infrastructure of a country and especially referring to countries with financial limitations such as Greece in this particular time period. These limitations of on-site building energy production might be compensated though by off-site energy production. Since dense urban environments that promote and induce public transport and diminish commuting times have proven to be a sustainable urban model, then energy production could as well as be implemented outside the city limits where solar radiation for example might be less obscured by high-rises and land prices are lower. Also other energy resources like electricity production from wind farms in the sea could be an alternative. Thus, the definition of the European Union of a nearly zero-energy building or even a zero energy building, with a balanced trade between energy use and energy production, might be extended to off-site renewable energy sources.

ANSWERING THE RESEARCH QUESTION

To sum up, the answer to the research question of this Thesis is that through the integrated optimization of design and construction variables (energy production, optimized mechanical system set-points, adaptive comfort levels) the building’s energy performance is reduced by 33% (from 109.12 kWh/m² to 73.13kWh/m²) from the starting point of the current regulations in Greece as seen in figure 10.1. (The starting building refers to: wwr=40%/ wall Uvalue=0.5W/m²K / glazing Uvalue=2W/m²K / glazing Gvalue=0.5/ infiltration=0.2ach/ cooling setpoint= 26°C).

The aforementioned simulations were made with the maximum acceptable level for equipment load for the current Greek regulation (15W/m²). In most offices though, the equipment load is approximately 7.5 W/m² and since equipment loads represent a large part of the total energy use, the improved energy use due to equipment load reduction is 44.9 kWh/m² (fig 10.1) and refers to a further improvement of 38.6%.

Nevertheless, towards a potentially nearly zero energy building or even a zero energy building, more sophisticated measures might have to be taken, like atrium for improved natural ventilation, improved building management systems (BMS) and energy production systems with higher efficiencies. Also more efficient office equipment can lead to greatly reduced energy demands. Within the dense urban environment though, off-site energy production that would refer to a broader social and building spectrum might be beneficial towards the cause of energy use reduction in the building sector and climate protection.
FURTHER STUDIES

This study could serve as a starting point for further studies. This could entail improving the accuracy and broadening the variable spectrum of this study, of focusing in more detailed aspects of a building.

This study makes evident that the following aspects have room for improvement:

- Detect the level of accuracy for the calculations as trade-off between time and accuracy needed. The accuracy needed is also dependent on how broad the spectrum of optimized variables is.

- Add more design or construction variables that have conflicting effects on various energy loads.

- Implement this integrated methodology on various climatic conditions and compare the results of this integrated methodology to those of stepped strategies.

- Add the building shape, building orientation and various building installations in the integrated methodology process and point out the effects of these variables through a sensitivity analysis.

- Use this methodology for the optimization of more complex building models like whole buildings with non-repeating floor plans and add surrounding buildings that affect solar radiation and wind patterns.

- Add more objectives apart from energy use and thermal comfort such as visual comfort, that could be conflicting towards the goal of zero energy building.

- Combine the building energy and comfort optimization with other aspects of the building design such as structural optimization and detect the conflicting issues.

- Implement this methodology with other software like Design Builder and define the effect on the accuracy of the results.
APPENDIX

Figure a.1: Climate Zones
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.1: Minimum energy performance requirements of building components
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012
Table a.2: Minimum energy performance requirements for the building envelope
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.3: Schedule of thermal zones
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.4: Temperature and relative humidity values for indoor spaces
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.5: Emitted heat from users
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.6: Required fresh air
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.7: Estimated thermal input of equipment
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.8: Lighting levels
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.9: Typical values of luminous efficiency of lamps
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.10: Typical values of power density per 100lux, for building audit
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

Table a.11: Hours of operation of a building during daylight (TD) and during the absence of daylight (TN)
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012
Table a.12: Coefficient of daylight effect due to automated control
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

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<tr>
<th>types of automated control for exploiting daylight</th>
<th>$F_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>manual control</td>
<td>1</td>
</tr>
<tr>
<td>automatic control</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table a.13: Characterization of the operation of installations: regarding the efficiency of cooling, heating (heat pump) the unit and the ability of performance of the rated cooling and/or thermal power
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

<table>
<thead>
<tr>
<th>cooling medium</th>
<th>performance coefficient for cooling (EER) and/or heating (COP)</th>
<th>deviation of performance compared to the rated power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>CFC</td>
<td>EER or COP &lt;1.5</td>
</tr>
<tr>
<td>Mediocre</td>
<td>HCFC</td>
<td>1.5-EER or COP &gt;2.8</td>
</tr>
<tr>
<td>Good</td>
<td>other than CFC and HCFC</td>
<td>EER or COP &gt;4</td>
</tr>
<tr>
<td>Very Good</td>
<td></td>
<td>&lt;5%</td>
</tr>
</tbody>
</table>

Table a.14: Factor of converting the energy consumption of the building into primary energy
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

<table>
<thead>
<tr>
<th>source of energy</th>
<th>factor of conversion into primary energy (kgCO2/Kwh)</th>
<th>emitted pollutants per unit of energy (kgCO2/Kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>natural gas</td>
<td>1.05</td>
<td>0.196</td>
</tr>
<tr>
<td>heating oil</td>
<td>1.1</td>
<td>0.264</td>
</tr>
<tr>
<td>electricity</td>
<td>2.9</td>
<td>0.989</td>
</tr>
<tr>
<td>liquid gas</td>
<td>1.02</td>
<td>0.238</td>
</tr>
<tr>
<td>biomass</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>district heating from the Public Power Corporation</td>
<td>0.7</td>
<td>0.347</td>
</tr>
<tr>
<td>district heating from Renewable Energy Sources</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table a.15: Efficiency of PV panels
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

<table>
<thead>
<tr>
<th>Types of PV panels</th>
<th>efficiency</th>
<th>reduction coefficients due to age</th>
<th>due to connection with secondary systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>monocrystalline</td>
<td>12-19%</td>
<td>1.0% for every year of operation</td>
<td>5%</td>
</tr>
<tr>
<td>polycrystalline</td>
<td>12-19%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin-film amorphous</td>
<td>4-7%</td>
<td>1.1% for every year of operation</td>
<td>5%</td>
</tr>
<tr>
<td>(a-Si)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CuInGaSe3)</td>
<td>6-11%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CdTe)</td>
<td>6-12%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>triple junction</td>
<td>23-24%</td>
<td>1.0% for every year of operation</td>
<td>5%</td>
</tr>
</tbody>
</table>

Table a.16: Indicative efficiencies of cogeneration heating/cooling and power units
Source: Ministry of Environment Energy and Climatic Change (MEECC), 2012

<table>
<thead>
<tr>
<th>type of cogeneration unit</th>
<th>rated electrical power (kW)</th>
<th>electrical efficiency rate (%)</th>
<th>thermal efficiency rate (%)</th>
<th>total efficiency rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel cells</td>
<td>3-30</td>
<td>20-30</td>
<td>25-35</td>
<td>45-60</td>
</tr>
<tr>
<td>Stirling engine</td>
<td>3-100</td>
<td>35-45</td>
<td>50-60</td>
<td>80-85</td>
</tr>
<tr>
<td>OTTO engine</td>
<td>15-1300</td>
<td>32-35</td>
<td>50-60</td>
<td>80-85</td>
</tr>
<tr>
<td>DIESEL engine</td>
<td>100-20000</td>
<td>35-45</td>
<td>40-45</td>
<td>70-80</td>
</tr>
<tr>
<td>microturbine</td>
<td>25-20</td>
<td>25-35</td>
<td>40-50</td>
<td>70-80</td>
</tr>
<tr>
<td>bloossteam turbine</td>
<td>500-100000</td>
<td>25-30</td>
<td>40-60</td>
<td>60-80</td>
</tr>
<tr>
<td>gas turbine with heat recovery boiler</td>
<td>100-300000</td>
<td>25-35</td>
<td>40-50</td>
<td>70-80</td>
</tr>
</tbody>
</table>
LITERATURE


Building physics, lecture notes 2016 Lecture 1: Heating up a building with earth ducts, solar collectors and other time-independent mass flows, Tu Delft, 2016


