Zero energy potential of a high-rise office building in a Mediterranean climate

Using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings

Giouri, Evangelia Despoina; Tenpierik, Martin; Turrin, Michela

DOI
10.1016/j.enbuild.2019.109666

Publication date
2020

Document Version
Final published version

Published in
Energy and Buildings

Energy & Buildings 209 (2020) 109666

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Zero energy potential of a high-rise office building in a Mediterranean climate: Using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings

Evangelia Despoina Giouri*, Martin Tenpierik, Michela Turrin

Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, the Netherlands

ARTICLE INFO

Article history:
Received 25 August 2018
Revised 10 June 2019
Accepted 1 December 2019
Available online 2 December 2019

ABSTRACT

Currently 40% of EU's final energy consumption is attributed to buildings. Achieving the EU's climate targets would entail improved strategies in designing nearly Zero Energy Buildings. This research aimed to create an integrated decision-making strategy in designing ZEBs with the use of multi-objective optimization of building design and construction parameters for minimizing energy demand, while maximizing energy production and adaptive thermal comfort. Goal is to define which parameters have the highest impact and potential for further optimization and to offer an alternative to current stepped strategies such as the New Stepped Strategy. The proposed integrated approach is applied on a typical high-rise office building in Greece. Energy simulations with DesignBuilder are used as benchmark for the optimization run with EnergyPlus through Rhino and Grasshopper software via the plug-ins Honeybee and Ladybug, coupled with modeFRONTIER. For the first optimization round, the investigated parameters are: window-to-wall ratio, wall U-value, glazing construction U-value, glazing g-value, air-tightness of the facade, cooling set-point of the mechanical cooling system and PV facade surface area. For the second round, the parameters of window-to-wall ratio, shading area and PV surface area are adapted for four facade orientations. The optimizations resulted in a building with an annual final energy reduction of 33%.

1. Introduction

Within an urbanizing environment where 66% of the world's population is projected to be urban by 2050 [27], the need to reduce global CO_2 emissions is becoming apparent. Currently in the EU nearly 40% of final energy consumption and 36% of greenhouse gas emissions are attributed to buildings [2]. In order to achieve the EU's 2020 targets in the EPBD Directive, but also to meet the longer term objectives of the climate strategy of the low carbon economy roadmap 2050, optimized strategies in designing nearly Zero Energy Buildings (nZEBs) and high-rise nZEBs need to be developed. A zero energy building refers to a building that produces as much energy as it consumes in a defined period.

The existing stepped strategies such as the Trias Energetica [15] and the New Stepped Strategy [28] optimize design variables and especially passive and active design systems in a stepped approach. The New Stepped Strategy does so by including principles for closing cycles in the built environment. However, these approaches and many others are qualitative in nature. The design of a ZEB entails parameters that have conflicting influence on various energy loads and thermal comfort levels. Moreover, some parameters can have minimal influence on energy loads compared to others. In order to investigate the potential for improvement and trade-off designs that optimally solve conflicting problems, an extensive quantitative data analysis of multiple designs and an integrated optimization of various conflicting passive and active systems are needed. Thus, this study introduces the implementation of an integrated strategy through multi-objective optimization of various building design parameters, that could result in a highly energy-efficient and thermally comfortable building, through steering resources in directions that have more potential for improvement and thus could also lead to more affordable ZEBs. As the brief literature review in the next section will show, several studies argue for the need for better integrated quantitative strategies that can aid the design process of high performance buildings. Some of these studies have already applied a basic optimization strategy based on single or multi-objective optimization. However, practically all of these studies focused on small relatively simple buildings of mostly a few stories high and / or did not include a

* Corresponding author: Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, the Netherlands

E-mail address: edgiouri@gmail.com (E.D. Giouri).

https://doi.org/10.1016/j.enbuild.2019.109666

thorough analysis of the design space. Particularly such an analysis of the design space is crucial for a quantitative integrated approach, because it on the one hand allows to check the validity of the results and on the other hand allows for showing which parameters are impacting the energy use of the building and its indoor comfort mostly. Particularly these parameters require most attention during the design process.

The main objective of this study [8], is to propose an integrated strategy for the early design phase of a ZEB, which contrary to existing stepped approaches, entails the algorithm aided, multi-objective optimization of potentially conflicting passive and active design parameters. The objectives refer to minimizing energy demand, while maximizing energy production and adaptive thermal comfort levels. The implementation of the proposed integrated strategy aims to help the designer take informed decisions in shaping an early-phase design strategy, as a set of measures, towards achieving a ZEB. The proposed integrated strategy is tested on a typical central-core, open plan, high-rise office building for the hot-summer Mediterranean climate (Csa) of Athens, Greece. Therefore the study aims to answer the following questions:

- 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 ZEB high-rise building in a hot-dry climate?
- How do different parameters of the most efficient design strategy influence different aspects of final energy and thermal comfort in the building?

The proposed integrated strategy and its computational set-up is generic and can be applied to various building typologies and climatic zones. Nonetheless, in this research, the integrated strategy is applied on a building, that is representative of a typology largely applied on high-rise office buildings, that of a central core open-plan office building. Therefore the results of this research can be extrapolated as measures towards ZEBs of this typology in the climatic zone investigated.

The performance indicators for the optimizations refer to annual final energy and adaptive thermal comfort levels. The first entails annual energy demand for cooling, heating, lighting and equipment and annual energy savings as energy production from PV panels. The latter is translated as the percentage of time, for an annual period, at which comfortable conditions occur when the indoor temperature is within the comfort range determined by the prevailing outdoor temperature. This study focuses on the decision-making design phase of a new building, thus the choice of the parameters optimized aims to extract the trends that indicate the elements of a building that have more potential for further improvement, towards creating a ZEB. The aforementioned performance of a building regarding the indicators can be affected by the shape and orientation of a building. Additionally, parameters affecting the performance can be the window to wall ratio, the wall U-value, the glazing construction U-value, the glazing g-value, the air-tightness of the facade, the shaded area of the openings, the cooling set-point of the mechanical cooling system and the surface area of photovoltaic panels on the facade. The following literature review indicates building parameters optimized towards energy-saving solutions for buildings.

2. Overview of previous studies

The optimal combination of parameters that lead to the design of a nearly zero energy building can be attained through multi-objective optimizations towards a thermally comfortable and energy-efficient building. The following studies are related to this concept.

2.1. Review on optimization studies

Xu et al. [29] aimed to minimize heating and cooling loads of an office space in Seoul using optimization driven by NSGA-II. The following parameters were investigated: floor area, building orientation, ceiling height, aspect ratio, plenum height, window-to-wall ratio, wall insulation, window insulation, solar heat gain coefficient and air leakage. The influence of HVAC systems was also investigated and it was concluded that different heating and cooling systems led to a different optimum building design.

Aim in the study of Yu et al. [31] was to find the optimal solution for a residential building in Chongqing, China, with regards to energy consumption and indoor thermal comfort. The optimization was driven with NSGA-II and EnergyPlus was used for energy simulations. Several design variables were investigated like floor area, orientation, shape, wall and roof heat transfer coefficient, wall and roof thermal inertia index, window heat transfer coefficient, and window to wall ratio for various orientations.

Hamdy et al. [9] used multi-stage optimization to develop a cost-optimal and nearly-zero-energy building. The aim was to find optimal combinations of 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. A single-family house was simulated with MATLAB and TRNSYS software aided by a variant of the genetic algorithm NSGA-II.

Evins et al. [6] explored the trade-off between cost and carbon emissions, for the design of a modular hotel unit. An optimization was applied for various climate types. Investigated variables were envelope design parameters, different HVAC systems and energy generation from PV and solar thermal panels installed on the roof.

The need of optimization for improving building and HVAC system performance was underlined by Holst [10]. In his optimization for a school building in Trondheim, Norway he explored both passive and active design aspects. The later entailed night setback temperatures.

In a design optimization of insulation and space conditioning load, Shi [24] aimed to find a balance in the objectives. The case study is a one-story office building in Nanjing, China, with 3 thermal zones: a conference room and 2 office spaces. modeFRONTIER was used as optimization platform coupled with EnergyPlus for simulation of the space conditioning load.

Loonen et al. [14] explored the potential of Climate Adaptive Building Shells by using building performance simulation and optimization. The objective was to balance energy demand and thermal comfort, by minimizing the sum of heating and cooling energy demand and the number of hours per year that temperature exceeds 25 °C. Static office building shell designs were investigated for a short-term period and a long-term period. The non-dominated sorting genetic algorithm II (NSGA-II) drove the optimization.

Chantrelle et al. [4] used a genetic algorithm (NSGA-II) coupled with TRNSYS for the renovation of a school in the southern French. The optimization objectives were annual energy consumption (cooling, heating, lighting and ventilation), thermal comfort, cost and environmental impact. The investigated variables were various types of external wall, roof, ground floor, intermediate floor, internal wall and window types.

Caldas [3] used GENE_ARCH to optimize the building geometry in several applications, dealing with issues of energy demand, materials, costs, and lighting behavior.

The need for multi-objective optimization in early design stages was highlighted by Negendahl and Nielsen [19]. Their research focused on the design of a specific facade pattern, based on the optimization of energy use, capital cost, daylight distribution and thermal loads.

Manzan [17] used genetic optimization to find a geometry for external, fixed, shading devices with low energy and cost impact. The optimization modified shading device height, width, angle, distance from the wall and various glazing properties for an office room in Trieste and Rome. Thermal load simulations were run with ESP-r and illuminance simulations with DAYSIM. The optimization was driven by modeFRONTIER, with the NSGA-II genetic algorithm.

The overview of optimization studies indicates the need for applying early-stage optimization for various building design and construction parameters, as well as for HVAC systems and energy generation from renewable sources in an integrated manner. Nevertheless, the overview indicates that only a few studies examine a broad range of variables, while including passive and active measures (Xu et al. [29], Evins et al. [6], Holst [10]). Those who focus on a limited spectrum of variables, may lack in investigating the interrelations and reciprocal influences deriving from an integrated approach.

2.2. Review on ZEB strategies

In 1996 Lysen [15] presented a stepped environmental design approach for energy called the Trias Energica. The 1st step aimed to prevent the use of energy. The 2nd step refers to using renewable energy sources as widely as possible. The last step relates to the remaining energy demand and entails using fossil fuels as efficiently and cleanly as possible [11].

Another stepped strategy is The New Stepped Strategy that eliminates the use of fossil fuels in exchange of the exploitation of waste flows [13]. The 1st step includes passive strategies such as shading or improved insulation of the building envelope. The 2nd step includes reusing and recycling waste flows, like exchanging heat between different buildings or functions. The 3rd step refers to producing energy from active systems like PV panels or solar collectors.

With regard to the Climate Responsive Design approach, according to Looman [13], the design should exploit natural energy sources like the sun, earth, wind, sky, water, complemented with energy recovery from waste flows. A combination of techniques will result into a low-energy, comfortable building.

The passive house strategy is based on the principles of reducing losses and optimizing passive solar gains, without the use of active systems [22]. The strategy refers to optimizing variables like the U value of external walls, roofs, shading surfaces, window area, etc. individually, in a stepped approach [21]. This process may require a minimized number of simulations, but the result may not be optimal due to the conflicting influence that many variables can have on various energy loads. For example, large windows may lead to increased daylight exploitation, but the increased solar gains can lead to overheating, especially in the summer.

The active house strategy entails comfort, energy and environment considerations. Comfort among others includes daylight, thermal comfort and air quality. The energy aspect refers to energy demand reduction, using renewable energy and minimizing use of energy from fossil origin [1]. This strategy suggests optimizing variables like window size, shading and thermal mass and others for maximizing thermal comfort. Optimizing the energy aspect includes optimizing wall U value, building orientation, infiltration, using natural ventilation and increasing daylight availability [1]. The approach used to implement this strategy is a stepped one, by optimizing aspects like daylight access, thermal comfort, renewable energy sources and envelope design variables separately.

A question arises as to how can the designer find the trade-off point between maximizing daylight exploitation, thermal comfort and energy production from RES (renewable energy sources) while minimizing energy demand. For example, large windows mean increased daylight exploitation, but minimize the opaque wall area for integration of PV panels on the facade, thus reducing energy production from RES. Also depending on the climatic zone, thermal comfort and thermal loads are affected positively or negatively by large windows.

From the review of existing ZEB strategies, it is apparent that designing a ZEB includes among others, objectives like maximizing thermal comfort and daylight access and energy production from RES, while minimizing energy demand. These objectives can be variably conflicting depending on the climatic conditions of the building site. Thus a stepped approach may not lead to the most optimal design regarding all the aforementioned objectives.

2.3. The adaptive thermal comfort approach

Nicol and Humphreys [20] indicated that the adaptive comfort model, which is relying on the occupants' tendency to adapt to the building's outdoor conditions, allows the designer to calculate thermal comfort levels especially in naturally ventilated buildings. The authors also suggested the use of the adaptive model for mechanically cooled or heated buildings, with the aim of calculating a variable set-point for the mechanical systems that is related to outdoor temperature. For mechanically conditioned buildings, the PMV/PPD model is generally used [20,25].

According to Teleghani et al. [25], the adaptive thermal comfort levels for a naturally ventilated building in the climate of Greece, can be estimated by both ASHRAE 55 and EN15251 standards, although discrepancies, due to differences between the standards, may occur.

For the climate of Athens, Greece, it was estimated that the outdoor conditions would allow the investigated building to be naturally ventilated for a large part of the year and thus the adaptive approach was selected for this research.

3. Methodology

The methodological scheme that shows the steps of this study is illustrated in Fig. 1. As a first step, the floor plan shape followed by building orientation optimization was implemented. Design Builder (Version 4.7.0.027) was used for a small number of energy demand simulations that served also as benchmark for the results of the following optimizations through Energy-Plus coupled with mode-FRONTIER.

For the implementation of the integrated strategy, two multi-objective optimization rounds of design and construction parameters that could have conflicting impact on cooling, lighting, heating energy loads, energy production from PV panels and adaptive thermal comfort levels were run. For each optimization round, 1000 different high-rise designs/ constructions were simulated. Implementing the integrated strategy into two separate optimization rounds that examine different variables helped to reduce the overall optimization time by reducing the possible combinations of parameter values. Energy simulations were run with EnergyPlus through McNeel Rhinoceros/ Grasshopper software via the plug-ins Honeybee and Ladybug [23]. Daylight simulations were run through McNeel Rhinoceros/ Grasshopper software with Daysim via Honeybee. The optimization was driven by modeFRONTIER with the genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm) that has been widely used in studies of building design optimization [16]. The objectives were to minimize energy demand, by minimizing cooling, heating and artificial lighting loads, to maximize energy generation from PV panels, while at the same time to maximize adaptive thermal comfort levels, for an annual period.

The parameters optimized for the first optimization round were the window to wall ratio, the wall U-value, the glazing construction U-value, the glazing g-value, the air-tightness of the facade,

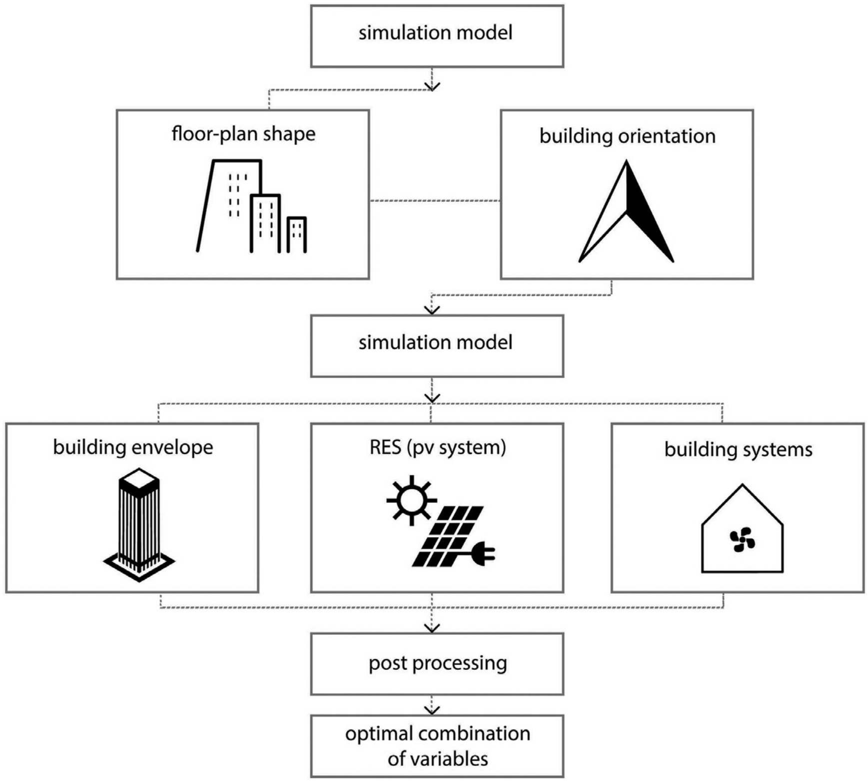

Fig. 1. Methodological scheme of the research.

the cooling set-point of the mechanical cooling system and the PV facade surface area. For this first optimization round, one optimization was implemented without energy generation from PV panels and one including energy generation, since the PV façade area is investigated through the window to wall ratio variable. For the second optimization round, the parameters of the window to wall ratio, shading area and PV surface area adapted to each facade orientation (North, South, West, East) were optimized.

Data analysis through charts for the various energy loads and adaptive thermal comfort levels for the 1000 building designs was implemented. Analyzing the graphs and implementing a sensitivity analysis indicated the impact of the various facade parameters on the final energy and adaptive thermal comfort performance of the building.

3.1. Reference building

The tower of Piraeus is selected as a design reference and starting point for the optimization. This building is selected because it is a typical central core, open plan, high-rise, office building with usable open-office space in the peripheral floor plan and repeating floor plans (Fig. 2). This design starting-point is representative of a larger spectrum of buildings that belong to the aforementioned typology, which is largely applied on high-rise office buildings. Located in the port of Piraeus in Athens, Greece, it is a 22-storey building of 84 m height and 45.42 × 27.26 m rectangular floor plan. The facade is made of steel and glass. The bearing structure is made out of steel reinforced concrete.

3.2. Climate data

The building is located at the port of Piraeus in Athens. With 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 (414.1 mm yearly precipitation on average) [7]. In winter, temperatures by day reach 14.2 °C on average. At night the temperature falls to 7.7 °C. Spring temperatures reach 19.7 °C during the day. During summer temperatures vary between 21.8 °C and 30.5 °C. Highest mean direct normal radiation levels are recorded in the summer months, ranging from 6000 to 7000 Wh/m^2 per day. Hourly weather data for Athens from the report "GRC_ATHENS_IWEC" [5] are used for all the simulated models.

3.3. Simulated building models

For this research two model types were created, one for the Design Builder software and one for the McNeel Rhinoceros/ Grasshopper software. Transitioning from the case study design to the simulation model in Design Builder, several simplifications needed to be implemented for reducing simulation time. The existing building has 2 cores, for the simulation 1 closed core area is simulated. The model consists of 31 floors of 3.26 m height (Fig. 3). The input data in Table 1 are used to run the simulations and are based on the current national standards of Greece for office buildings [18]. The simulation period is annual. Internal floors and partitions of the core are adiabatic. The simulated models refer to buildings with a mixed mode ventilation system that use both mechanical and natural ventilation.

The Grasshopper model consists of 5 different zones (Fig. 4): the core, and 4 zones. The longest zones have South and North orientation while the shortest have West and East orientation. The dimensions of the floor plan (Fig. 4) are the same as the rectangular Design Builder model (Fig. 3). The input data for the first optimization round in Table 2 rely on the national Greek regulation for offices [18]. The results of the variables optimized in the first round serve as input for the second round. The simulation period is annual. Energy-Plus was used via Honeybee [23] for energy performance and energy generation simulations. Daysim was used via

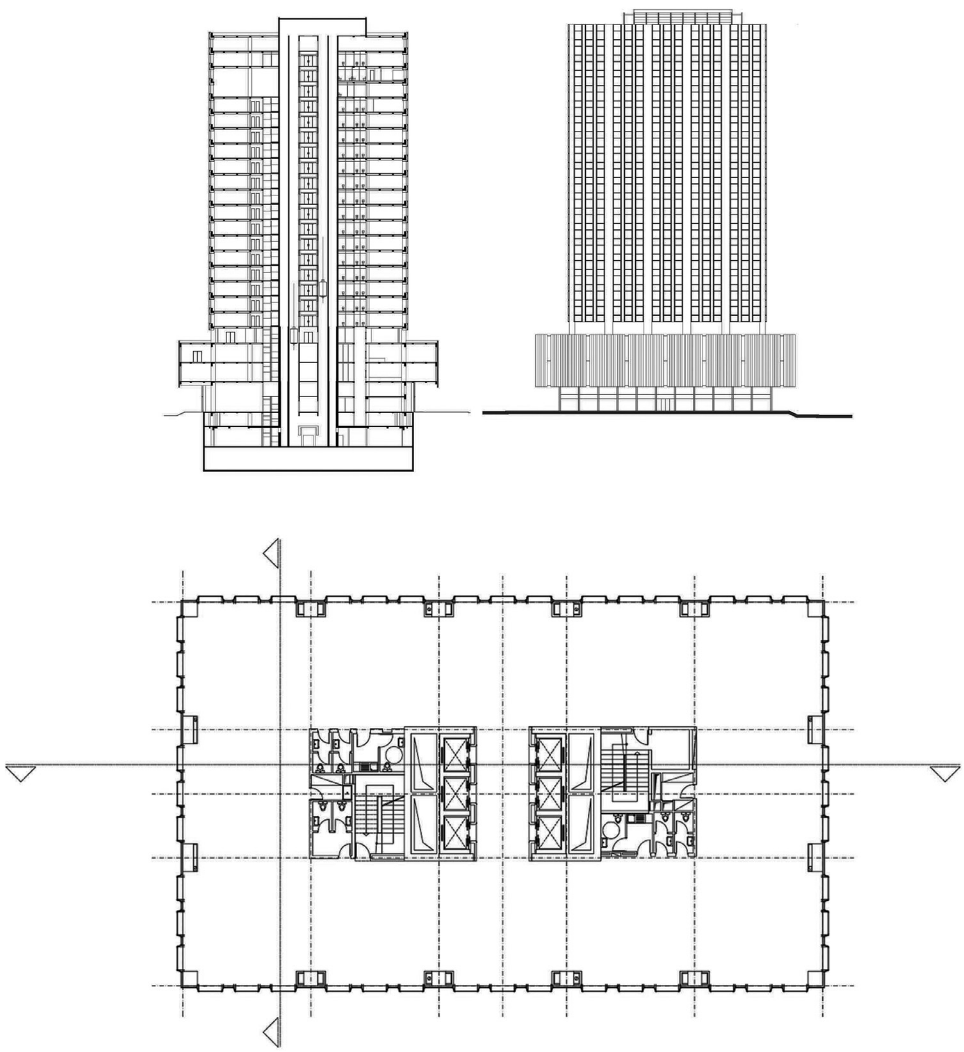

Fig. 2. Case study building plans, from upper left corner clockwise: section, elevation and typical floor plan.
Source: Source greekarchitects.gr/competition2010, 2010 [12].

Table 1
Input details of building model for Design Builder.

Building parameter	Unit	Value
Occupancy density	persons/m²	0,1 [18]
Computers load	W/m²	15 [18]
Heating set-point	°C	20 [18]
Cooling set-point	°C	26 [18]
Natural ventilation set-point	°C	24
Minimum fresh air	m³/h/person	30 [18]
Air-tightness	ac/h	0,2 [18]
External wall U-value	W/m²K	0,35 [18]
External wall costrution	_	(out to in) 100 mm brick/79.5 mm extruded polysterene/100 mm concrete/13 mm gypsum
Roof U-value	W/m²K	0,25 [18]
Roof construction	_	10 mm asphalt/144.5 mm glass wool/200 mm air gap/13 mm plaster
Floor construction	_	100 mm cast concrete (dense)
Ground floor U-value	W/m²K	0,25 [18]
Internal partition U-value	W/m²K	1,923
Window-to-wall ratio	%	30
glazing type	_	double glazing 6 mm/13 mm/6mm
Glazing U-Value	W/m²K	1,499 [18]
SHGC	_	0,564
Normalized power density for artificial lighting	W/m²–100lux	3,2 [18]
Heat recovery	_	on
HVAC system	_	VAV/Water cooled chiller/full humidity control

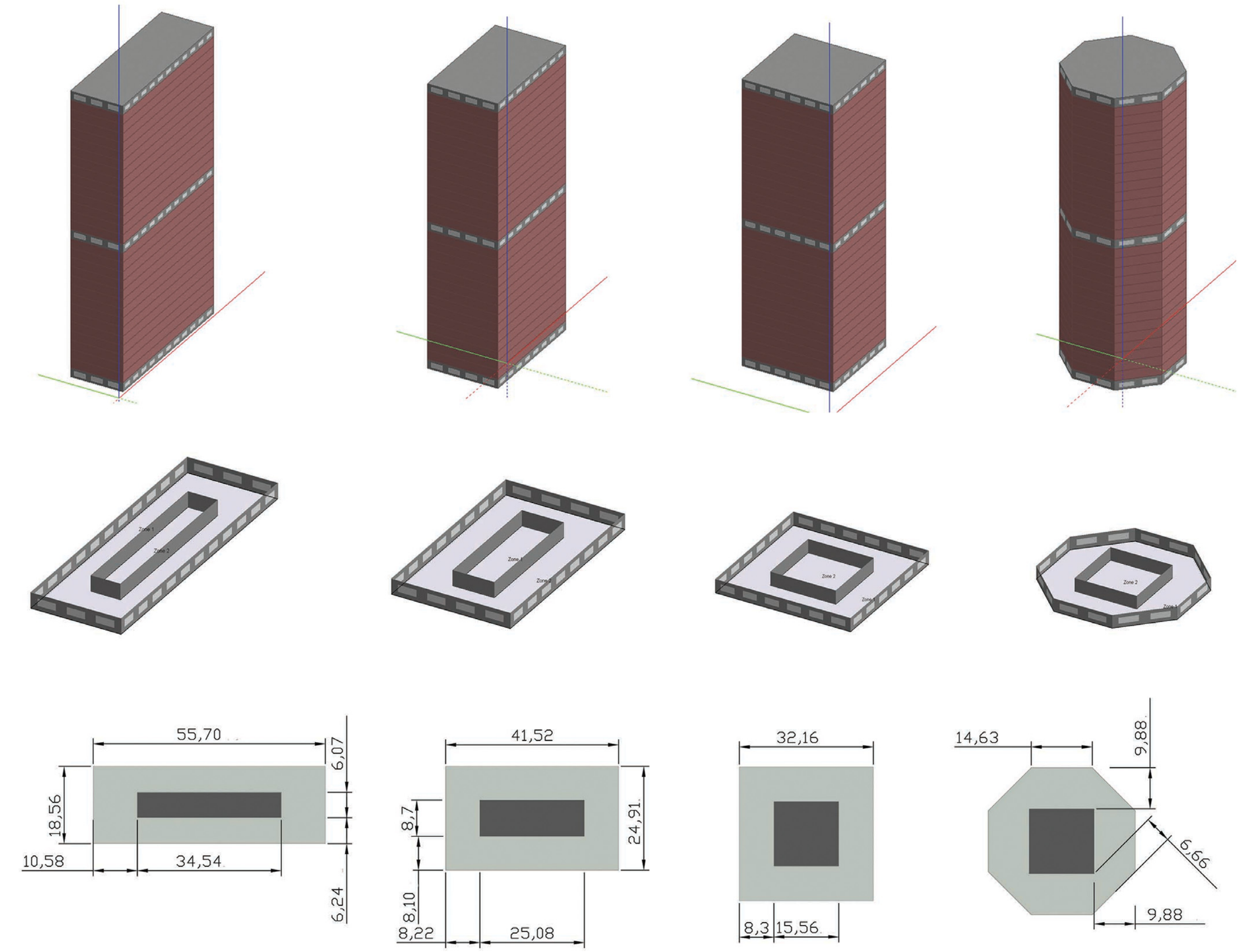

Fig. 3. Design Builder models and floor-plan dimensions.

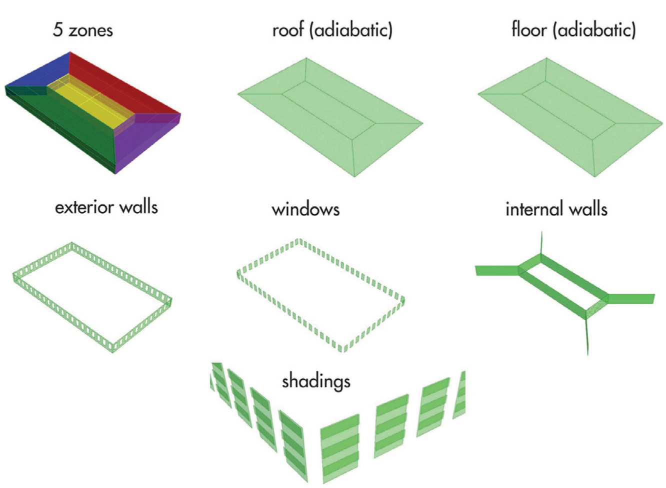

Fig. 4. Grasshopper model.

Honeybee for annual daylight simulations. For the calculation of adaptive thermal comfort levels, the adaptive model as integrated in Ladybug was used [23]. For the first optimization round, the ASHRAE 55 2013 was used as the adaptive thermal comfort standard, whereas the EN15251 standard was used for the second optimization round. The models refer to a change-over, mixed-mode ventilation system, when one of the two options (natural ventilation or mechanical ventilation) is active at a specific time.

3.4. modeFRONTIER platform

In order to implement a multi-objective optimization and extract data from a large number of simulated designs, an optimization platform was used. The optimization was implemented with modeFRONTIER. ModeFRONTIER is an optimization platform that can drive an optimization loop using different applications. It allows to perform multi-objective optimizations and gives the option to select different optimization algorithms [17]. Rhino/Grasshopper and modeFRONTIER were connected using a link developed by ESTECO with TUDelft [30]. The number of simulated designs for both optimization rounds is 1000 each. The overall number of possible designs is related to the number of values of the variables. All possible combinations of designs if sampling were applied would be 1.944 different designs for the first optimization round and 160.000 for the second round. But, since an optimization is applied, the optimal solution is found earlier in the process. The time needed for the evaluation of 1000 designs was 44 h and 24 min. The evaluation time of 1 design was approximately 2′ 40′′. The optimization run on i7-5820 K, CPU at 3,3 GHz. The workflow of

Table 2
Input details of building model for EnergyPlus/Honeybee/Ladybug.

Building parameter	Unit	Value for optimization Round1	Value for optimization Round2
Occupancy density	persons/m²	0,1 [18]	0,1 [18]
Computers load	W/m²	15 [18]	15 [18]
Heating set-point	°C	20 [18]	20 [18]
Cooling set-point	°C	(variable)	26
Min indoor temperature for natural ventilation	°C	21	21
Max indoor temperature for natural ventilation	°C	23	25
Minimum fresh air	m³/h/person	30 [18]	30 [18]
Air-tightness	ac/h	(variable)	0,1
External wall U-value	W/m²K	(variable)	0,1
Floor construction	–	acoustic tile/50 mm insulation board/200 mm heavyweight concrete	acoustic tile/50 mm insulation board/200 mm heavyweight concrete
Floor U-value	W/m²K	0,4726	0,4726
Internal partition U-value	W/m²K	2,58	2,58
Window-to-wall ratio	%	(variable)	(variable per facade orientation)
Shading area	%	50	(variable per facade orientation)
Glazing U-Value	W/m²K	(variable)	1,8
SHGC	–	(variable)	0,3
Normalized power density for artificial lighting	W/m²–100lux	3,2 [18]	3,2 [18]
Heat recovery	–	on	on
HVAC system	–	"Ideal Loads"	"Ideal Loads"
PV system efficiency	%	12 [18]	12 [18]

the optimization in the interface of modeFRONTIER (Fig. 5) consists of the inputs, the outputs, the connection to Grasshopper, the Design of Experiments component and the optimization algorithm component. An algorithm widely used for energy optimizations of buildings is NSGA-II (non-dominated sortating genetic algorithm). In this study also this algorithm was used. Uniform Latin Hypercube is used as space filler with 25 numbers of initial designs and a Random Generator Seed value of 1.

4. Results and discussion

The following results refer to shape and orientation optimizations (Sections 4.1 and 4.2). Additionally, the results of the 2 integrated optimization processes reflect the effect of different variables on annual energy demand, energy production from PV panels and adaptive thermal comfort levels of the building (Sections 4.3 and 4.4). The results on annual energy demand refer to cooling, heating, artificial lighting and computer equipment loads.

4.1. Shape optimization

The first step is the optimization of the floor-plan shape. Aim is to define which shape leads to a more reduced energy demand of a high-rise open plan office building, with mixed mode ventilation system in Athens, Greece. This is realized by keeping the floor-plan area constrained, while gradually changing the shape from more compact to more elongated rectangular. The constraints are the total floor plan area (1034 m^2) and the area of the service cores (approximately 21% of the total area for the rectangular shapes and 23.4% for the compact shapes). The floor plan depth for the rectangular, square and octagon shapes is approximately 8.2 m, whereas for the elongated rectangular, the floor plan depth is minimized to 6.3 m, since the core should have realistic dimensions to fit the elevators, stairs and WC (Fig. 3).

Figs. 6–8 illustrate that cooling loads and lighting loads share the biggest part of energy consumption, whereas heating loads are nearly zero due to the climatic characteristics of Athens. For reducing cooling loads, compact buildings are favorable. In the graphs (Fig. 6) 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. More compact shapes with minimized facade surface lead to minimized solar gains and therefore to minimized cooling loads. Furthermore, the buildings are 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. Lighting loads are relatively diminished in the case of the elongated rectangular shape since it has a reduced floor plan depth and thus daylight has access to a larger floor area than the other options (Fig. 8).

The square building (Fig. 9) is marginally the best performing building with a value of 2029 MWh/a and the worst performing building is the one with the rectangular layout with approximately 2088 MWh/a. 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 within the specific climatic conditions of Athens, is negligible, therefore a designer could be free to explore various options.

4.2. Orientation optimization

For compact floor plans changing the orientation will have little effect on the energy demand. Also the elongated rectangular shape has a shorter floor-plan than many reference high-rise buildings like the Commerzbank high-rise in Frankfurt. Therefore, for the orientation optimization, the rectangular shape was chosen. For this

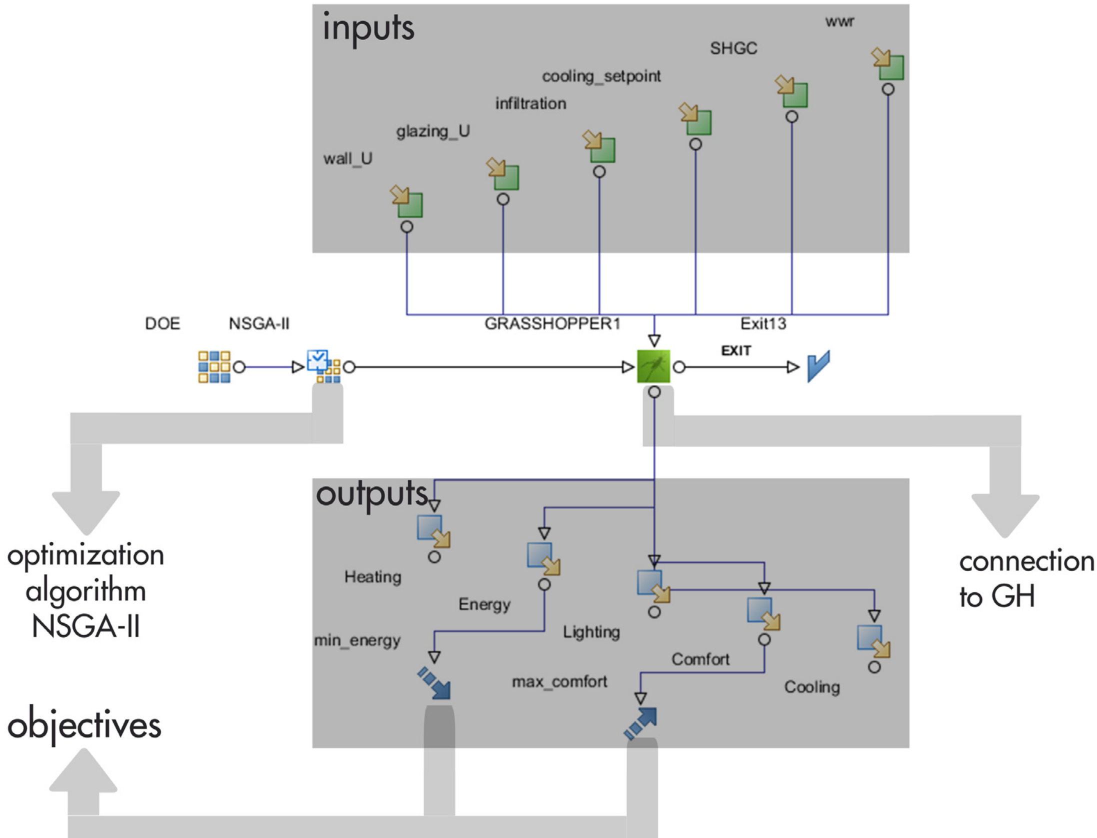

Fig. 5. Workflow in modeFrontier interface for 1st optimization round.

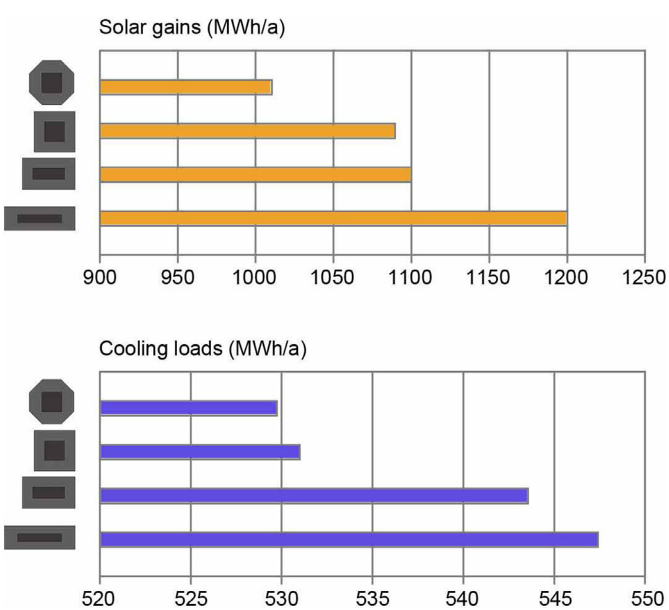

Fig. 6. Annual solar gain and cooling loads rankings for different plan shapes.

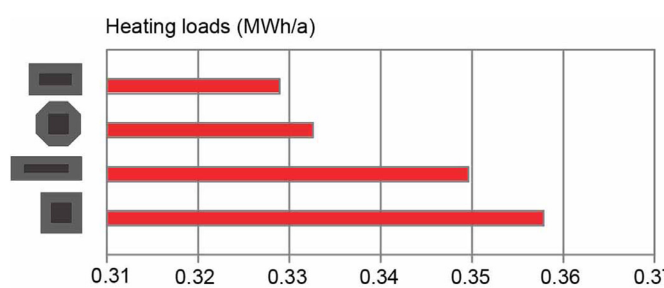

Fig. 7. Annual heating loads ranking for different plan shapes.

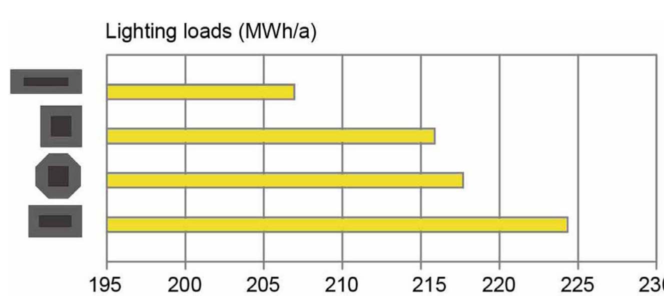

Fig. 8. Annual lighting loads ranking for different plan shapes.

step 4 different orientations were examined (North–South, East–West and Northwest–Southeast, Southwest–Northeast).

The solar gains chart (Fig. 10) indicates that greater exposure of the facade towards the east and west directions leads to increased solar gains, since the incidence angle is small, thus the solar radiation penetrates the whole floor plan. 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 steep incidence angle of the solar radiation limits the radiation from reaching deep in the floor-plan.

This step (Fig. 11) shows that the orientation of a building when there are no surrounding high-rise buildings, only affects to a minor degree the energy demand within the climatic conditions of

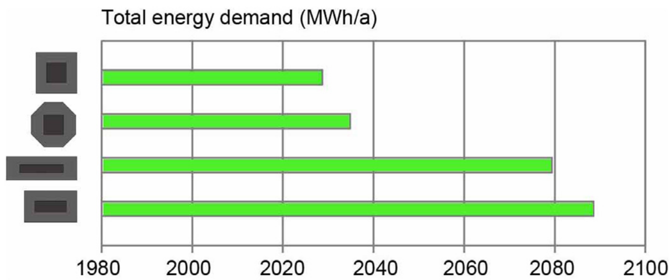

Fig. 9. Annual total energy demand ranking for different plan shapes.

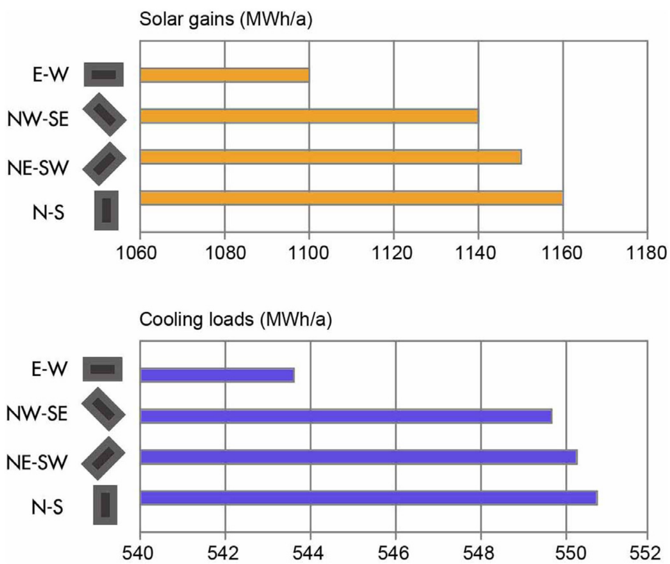

Fig. 10. Annual solar gain and cooling loads rankings for different orientations.

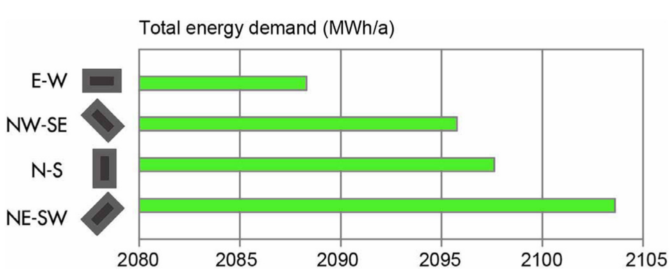

Fig. 11. Annual total energy demand ranking for different orientations.

Athens. Thus a designer is not highly restricted to adopt a certain orientation. Nevertheless, these optimizations were implemented on a high-rise building with no surrounding buildings. Surroundings with high-rise buildings at close proximity or different climatic conditions could possibly lead to different conclusions.

4.3. Integrated envelope, HVAC and energy generation multi-objective optimization

At this stage, a multi-objective optimization is implemented. Apart from reduced energy demand, also energy production and indoor thermal comfort of the occupants play an important role. The building envelope is the boundary between the indoor and outdoor environment. Therefore seven parameters were selected, five of which referring to the building envelope. The parameters examined were the window to wall ratio, the wall U-value, the glazing construction U-value, the glazing g-value, the air-tightness of the facade, the cooling set-point of the HVAC system and PV surface area in the facade.

To illustrate the trends of the impact of each parameter, within the spectrum of values tested, scatter plots are created. The following plots illustrate various building designs depicted as dots, colored according to the value of the variable with which it was simulated. Each design as dot is located relatively to the x and y axis according to their simulated performance on energy demand or final energy and levels of thermal comfort respectively. The optimal building designs are located on the Pareto front [26] (Fig. 12) of each plot, among which a designer can opt for the most energy efficient building, the most thermally comfortable design or a design with a trade-off performance between the two objectives.

4.3.1. Window to wall ratio (wwr)

For this variable, 6 different values were researched between 30% and 80%. A 30% wwr is expected to reduce cooling loads, but increase electric lighting loads, whereas an 80% window to wall ratio is expected to increase cooling loads and decrease electric lighting 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 first optimization round. The chart (Fig. 12) illustrates the effect of wwr on the energy demand and comfort levels. Small windows have a positive effect on reducing energy demand, but also increasing comfort levels in a building, since they lead to reduced solar heat gains and thus reduced cooling loads.

4.3.2. Wall U-value

For the external wall U-value of the building, 3 different values were simulated: 0.1, 0.2 and 0.3 W/m^2K. The 0.1 value refers to well insulated buildings and the 0.3 value to a less insulated building. It is important to mention that 0.3 W/m^2K is even better than the current national standards of Greece that allow a value of 0.5 W/m^2K for this climatic zone. Reducing the wall U values does not drastically improve the energy use or comfort levels of a building (Figs. 15–17). The reason is that the building is naturally ventilated as a result of which the thermal insulation is only effective during the hours when the windows are not open.

4.3.3. 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 were simulated: 0.6, 1.2 and 1.8 W/m^2K. The 0.6 $W/m^2/K$ refers to triple glazing, 1.2 $W/m^2/K$ to high performance double glazing and 1.8 $W/m^2/K$ to double glazing with a worse performance. The building simulated is naturally ventilated and the insulation of the openings is useful for the time-span that the windows are closed. In Fig. 17, the weak negative correlation indicates that higher glazing U-values lead to reduction of energy demand ($r = -0.376$) and increase of thermal comfort ($r = -0.213$). This could be interpreted as the need for the building to have improved natural ventilation like night cooling. The simulated model has concrete floors with high thermal mass. The heat is accumulated during the day in the concrete mass and is given off at night. With low glazing U value, the heat is trapped within the building with closed windows. In this case, constructions with a worst performing U value of 1.8 $W/m^2/K$ might drive the heat outside the building quicker than well insulating constructions.

4.3.4. Glazing g-value

For the g-value or solar heat gain coefficient (SHGC), 3 different values were 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

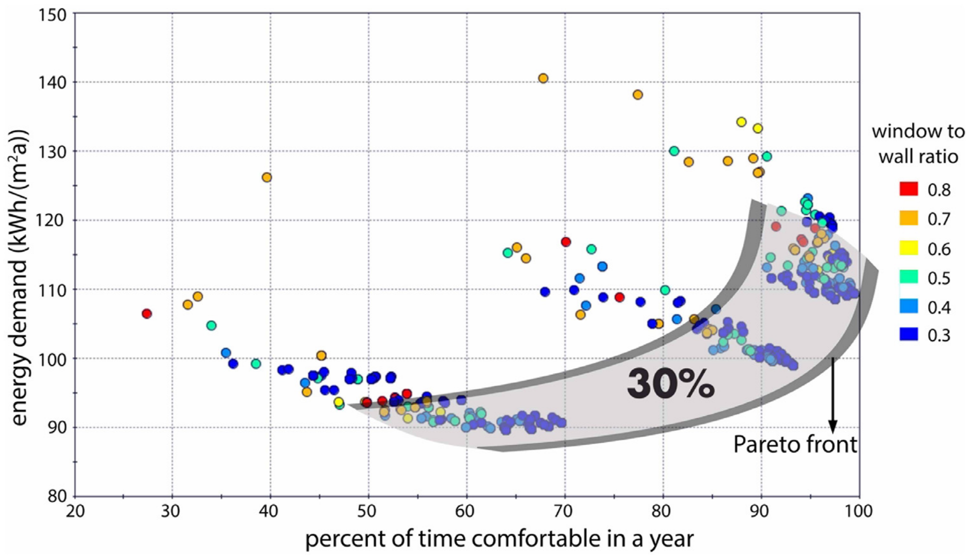

Fig. 12. Window to wall ratio effect regarding the objectives.

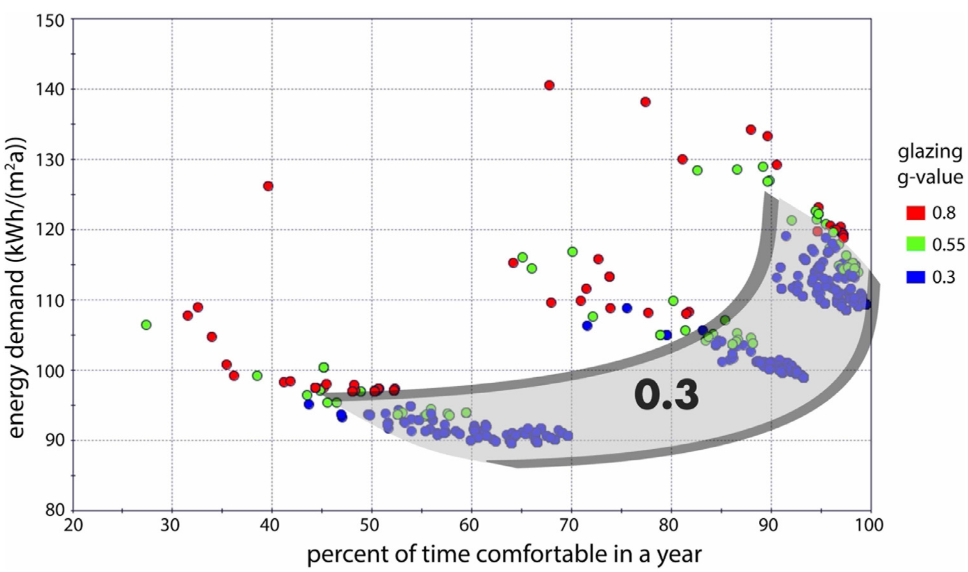

Fig. 13. Glazing g-value effect on the objectives.

reduce the total energy demand of the building. In Fig. 13 lower g-values tend to reduce the energy usage and improve comfort inside the building. Lower g-values mean that the building has less solar heat gains through glazing and therefore lower cooling loads.

4.3.5. Air-tightness

Air-tightness of the facade, or infiltration, allows for heat transfer between indoors and outdoors through the envelope in an uncontrolled way. The rate of the infiltration was investigated in this research with value steps: 0.1, 0.3, 0.5 and 0.7 air changes per hour. In Fig. 17, weak negative correlations show that low infiltration rates occur for designs with higher comfort levels ($r = -0.387$) and low energy use ($r = -0.293$), since air infiltration is an uncontrolled type of thermal/ventilation bridge.

4.3.6. Cooling set-point

Regarding the building services, this study focused foremostly on the energy demand thus not including the effects of different types of systems. The only building services related parameter investigated was the cooling set-point. Three values were examined: 24 °C, 26 °C and 28 °C. The cooling set-point refers to the indoor air or operative temperature above which the mechanical cooling system will start working. A value of 24 °C is expected to increase the comfort levels of the building, but also increase the energy consumption. In Fig. 14, the cooling set-point seems to have a drastic effect on the building's energy use and comfort levels. Cooling set-point of 28 °C reduces the energy use drastically, but also has a negative effect on comfort levels. A cooling set-point of 26 °C seems to have a balancing effect between comfort and energy usage.

4.3.7. PV facade surface area

This optimization variable is linked to the window to wall ratio. It refers to PV panels mounted vertically on all 4 facades of the building where no transparent windows exist. It is obvious that for lower glazing ratios of 30%, higher amounts of electricity will be generated and reversely, for high window to wall 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% wwr.

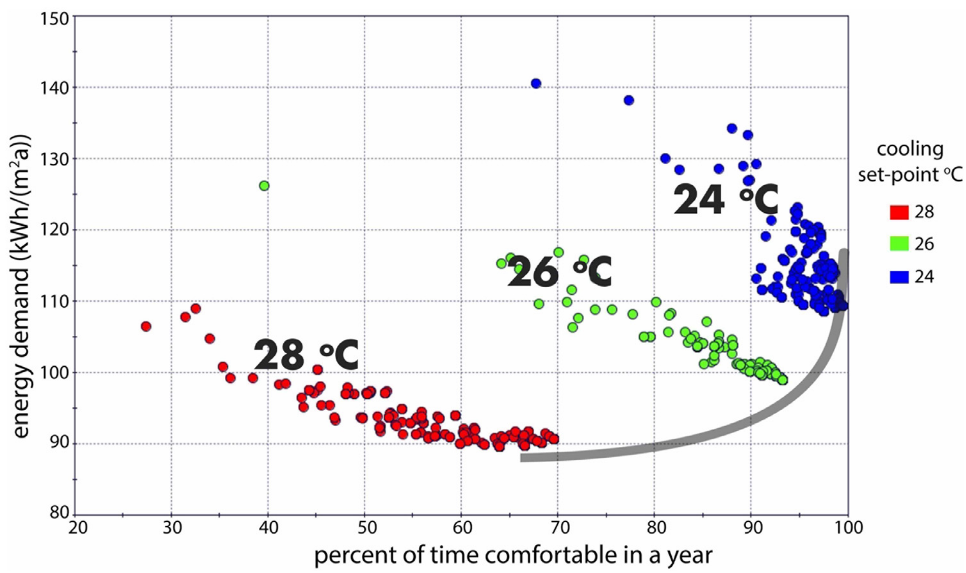

Fig. 14. Cooling set-point effect regarding the objectives.

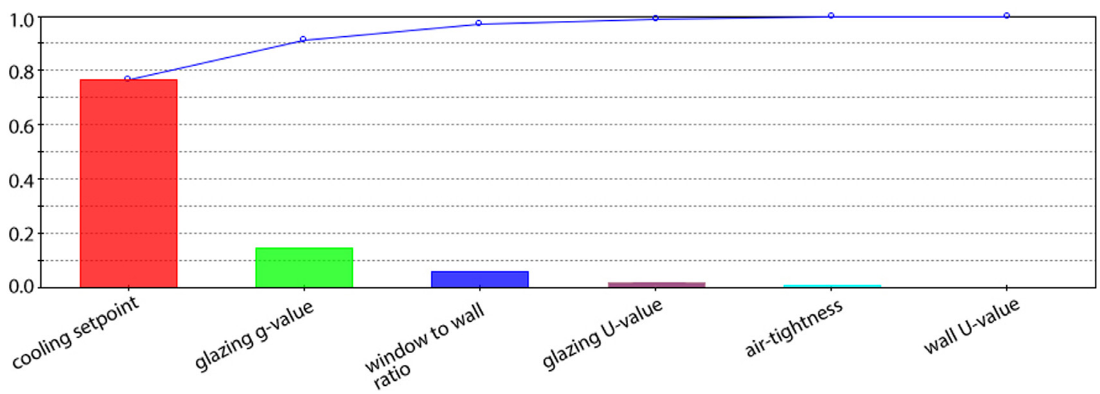

Fig. 15. Effect of variables on minimizing energy demand.

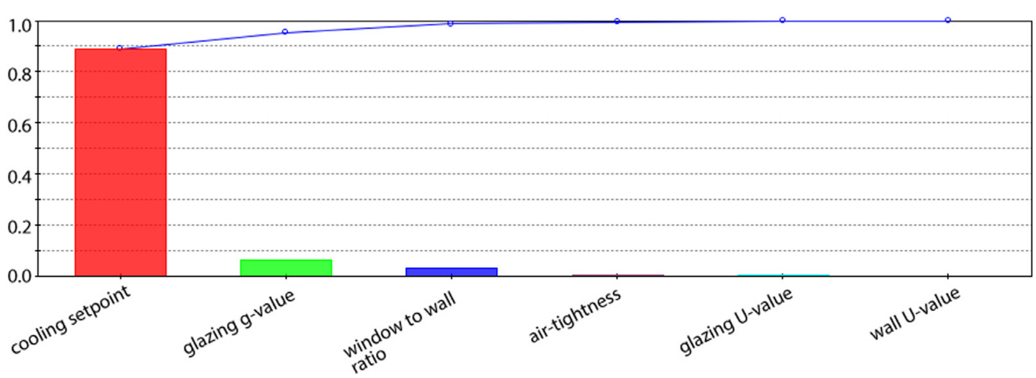

Fig. 16. Effect of variables on maximizing comfort.

Fig. 18 shows how the presence of energy generation systems reduces the annual final energy of the building by 17.5%. Small windows (30% wwr) in Fig. 19 have a positive effect on maximizing energy production, but also increasing comfort levels in a building.

4.3.8. Integration of envelope-HVAC-PV parameters

The correlation chart in Fig. 17 indicates that the objectives of minimizing energy demand 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 ($r = -0.902$). In the sensitivity analysis chart (Fig. 15) created with modeFRONTIER, it is apparent that the cooling set-point has the highest influence on minimizing the energy demand, followed by g-value and window to wall ratio. Regarding the window to wall ratio, note that the sensitivity analysis (Figs. 15–17), does not include the PV area optimization. Nevertheless, it is visible from Fig. 18 that the energy generation on the facade would increase even more the already positive effect of smaller windows in minimizing final energy. Glazing U-value, infiltration rate and wall U-value seem to have minimized influence on

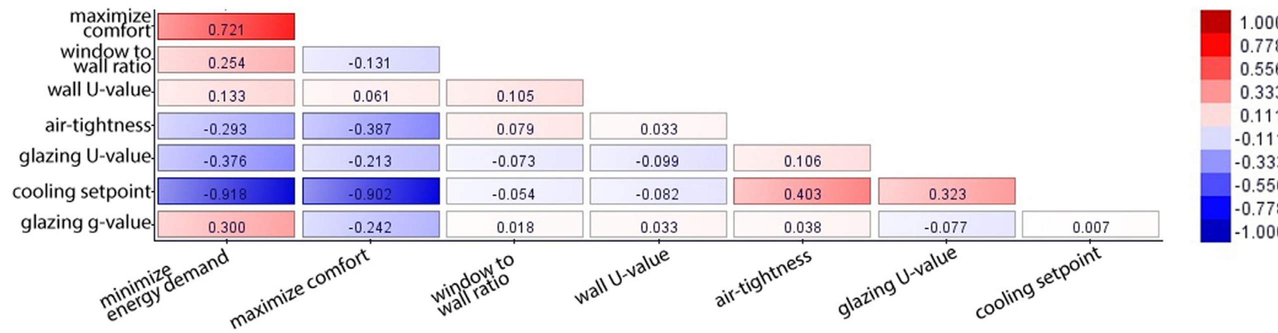

Fig. 17. Pearson correlation chart.

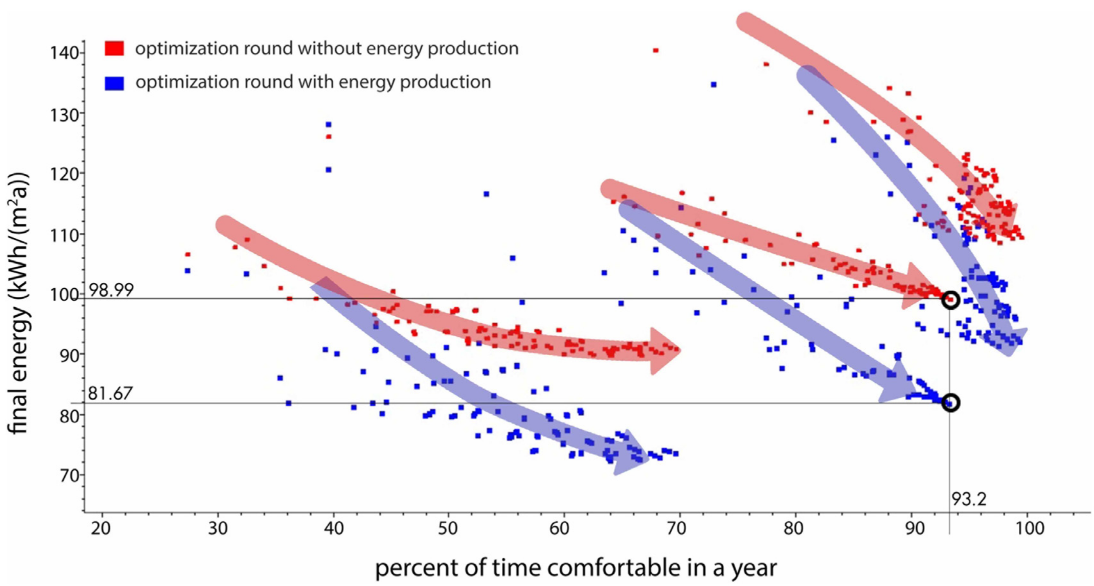

Fig. 18. Comparison of designs with energy generation optimization and without energy generation.

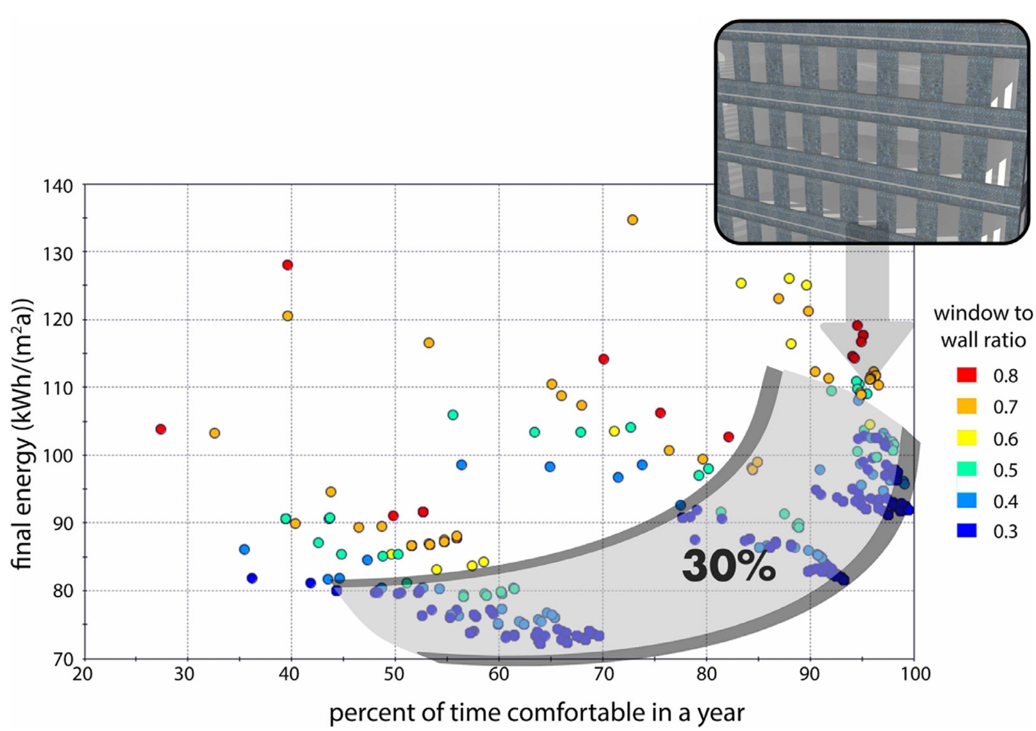

Fig. 19. Window to wall ratio effect regarding the objectives. including energy generation.

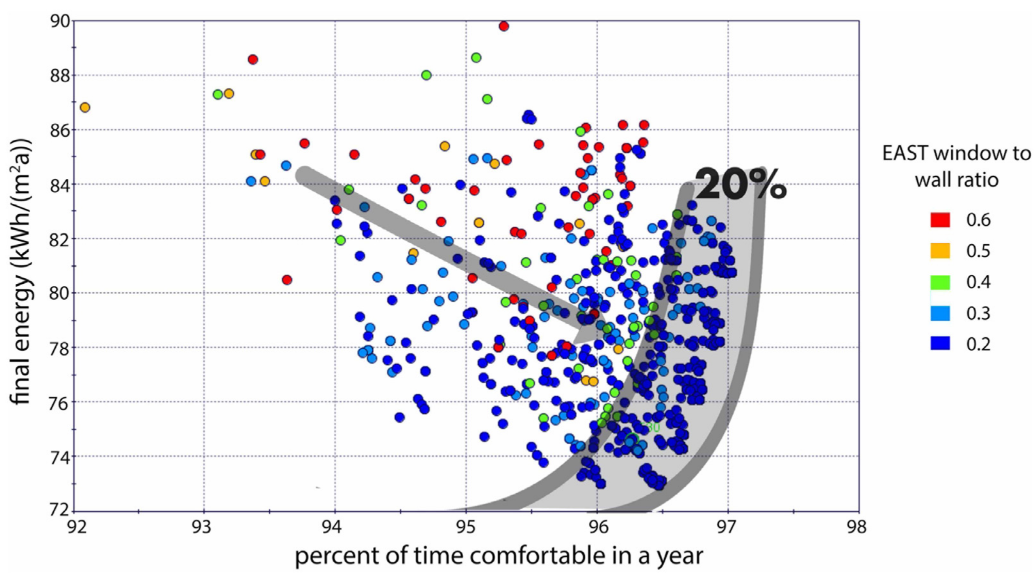

Fig. 20. East facade window to wall ratio effect regarding the objectives.

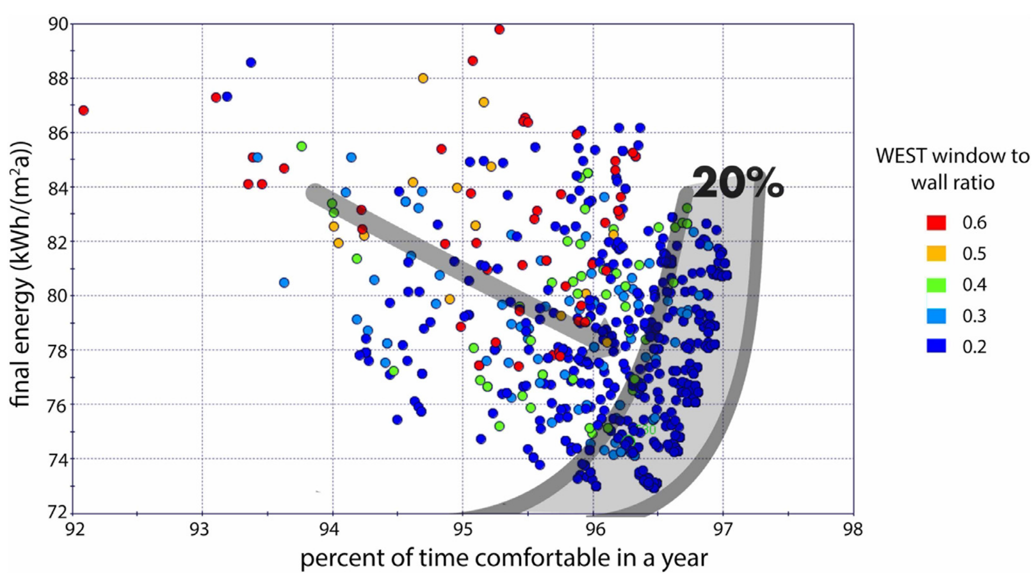

Fig. 21. West facade window to wall ratio effect regarding the objectives.

this objective. In the sensitivity analysis chart (Fig. 16) referring to the objective of maximizing comfort, cooling set-point is also the most influential factor for comfort, followed by g-value and window to wall ratio.

4.4. Integrated envelope and energy generation multi-objective optimization

To proceed to this optimization round, input data (Table 2) were used from the optimal design chosen (Fig. 18) in the previous optimization round. This building with final energy at 81.67 kWh/(m^2a) is chosen as the optimal trade-off solution between minimizing final energy and maximizing adaptive thermal comfort. This design's parameters refer to: wwr = 30%/ wall U-value = 0.1 W/m^2K / glazing U-value = 1.8 W/m^2K / glazing g-value = 0.3/ infiltration=0.1 ach/ cooling setpoint = 26 °C.

From the previous optimization it became clear that the window to wall ratio and solar control were the most important facade-related variables to consider. The second optimization therefore examined 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). These design aspects are directly related to the amount of solar heat gains in the building.

4.4.1. Window to wall ratio (wwr)

For this variable, 5 different values were investigated for each of the 4 facade orientations between 20% and 60% window to wall ratios. A 20% wwr is expected to reduce cooling loads, but increase electric lighting loads, whereas a 60% wwr refers to an almost fully glazed facade and is expected to have the opposite effect. Figs. 20–22 illustrate the effect of wwr of the east, west and north facade on the final energy and comfort levels. Small windows (20% glazed area) have a positive effect on reducing final energy and increasing comfort levels. They lead to reduced solar heat gains and thus reduced cooling loads. Additionally, minimizing final energy is aided with increased energy production from PV panels. Although smaller windows mean increased electric lighting loads due to reduced daylight exploitation, for the specific cli-

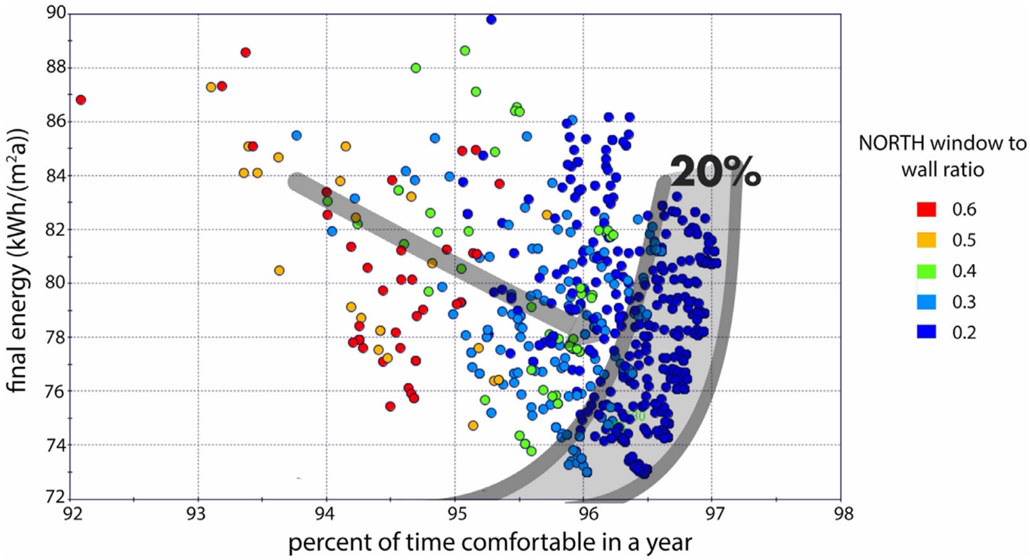

Fig. 22. North facade window to wall ratio effect regarding the objectives.

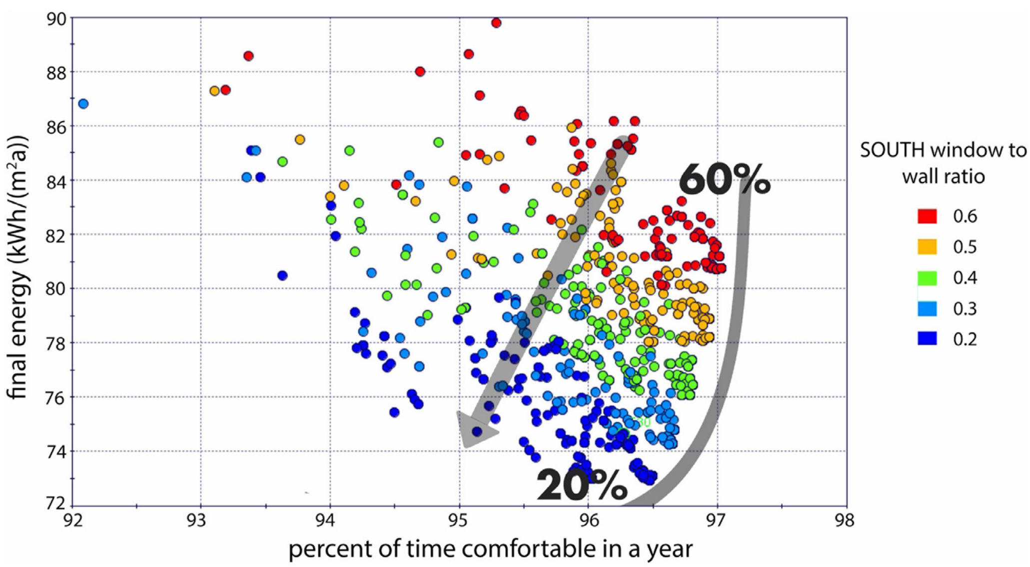

Fig. 23. South facade window to wall ratio effect regarding the objectives.

mate of Athens, this negative effect is compensated by the aforementioned solar heat gains reduction and energy generation. For the south facade (Fig. 23) on the final energy and comfort levels, larger windows (60% wwr) seem to lead to marginally improved comfort levels than smaller windows (20% wwr). Solar radiation from the South enters the building almost vertically and does not reach deep into the floor-plan, so the window area is not so important for the solar heat gains. Furthermore, bigger windows mean increased flow of natural ventilation and daylight admission. This leads to increased indoor thermal comfort levels and reduced demand for electric lighting (Fig. 24).

4.4.2. Shading area

For this variable, 4 different input values were set for each of the 4 facade orientations: 25%, 40%, 55%, 70% shaded area of the openings. This investigation refers only to external shadings. 25% shaded glazed area is expected to increase cooling loads, but reduce electric lighting loads. A 70% shaded glazed area is expected to decrease cooling loads and increase electric lighting loads. For the south orientation (Fig. 25), shading area of 25% is marginally better for energy demand and thermal comfort levels of the building. For the other orientations, the optimization of the shading area has much less influence on the objectives (Figs. 26–28) given the fact that the simulated models refer to a building with a g-value of 0.3 that blocks a large part of solar heat gains from entering the building, thus having a similar effect to shading. For this optimization, visual comfort is not taken into account, so the conclusions derived from this optimization are only referring to thermal comfort and final energy objectives.

4.4.3. Energy generation from photovoltaic panels

This variable is linked to the window to wall ratio. It refers to PV panels mounted vertically on the facades, on those parts where there are no windows. For lower window to wall ratios of 20%, higher amounts of electricity will be generated and reversely, for high window to wall ratios of 50% and 60%, the least amount of

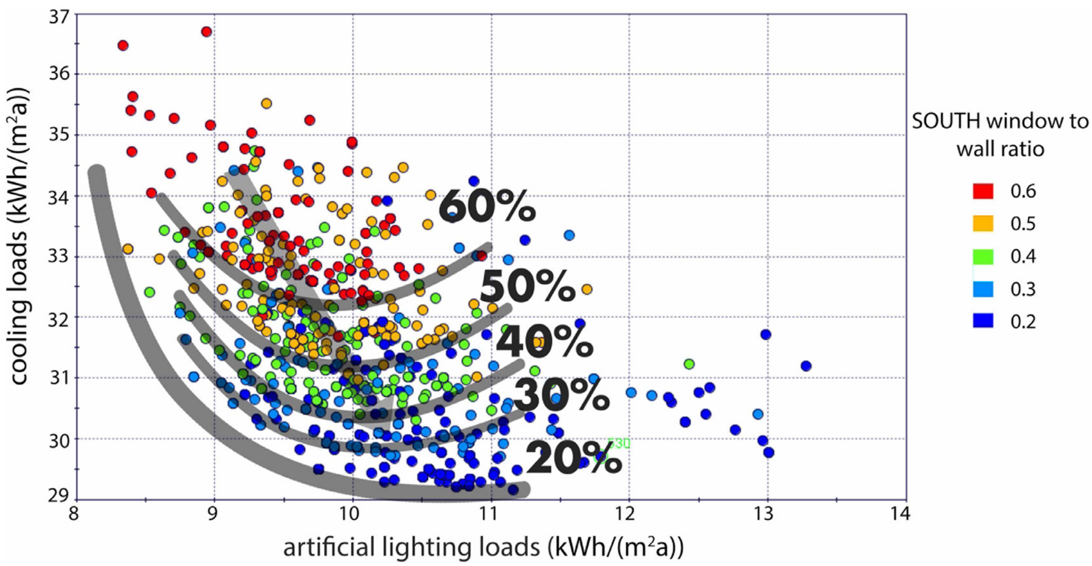

Fig. 24. South facade window to wall ratio effect on cooling and artificial lighting loads.

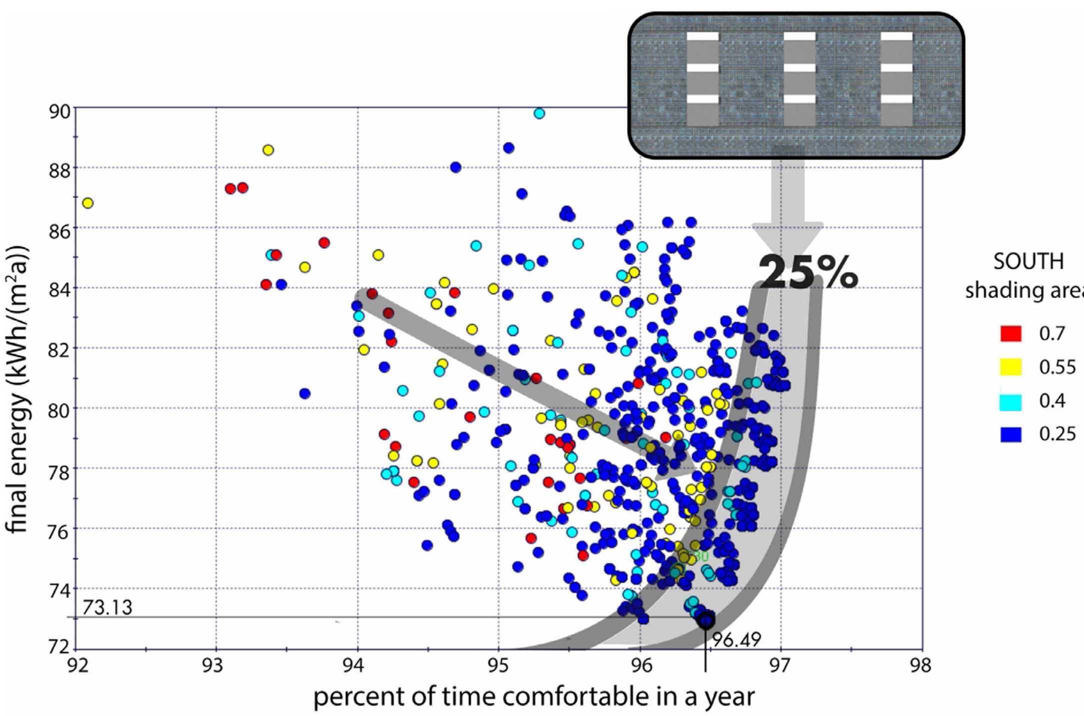

Fig. 25. South facade shading area effect regarding the objectives.

electricity will be produced. Nevertheless, glazing ratios of 20%, do not exploit daylight as well as a 60% window to wall ratio. In Fig. 24, optimal daylight exploitation is achieved with 60% wwr, that reduces the artificial lighting loads but the reverse is true regarding the cooling loads that are also predominant for the investigated climatic zone.

4.4.4. Integration of envelope-PV parameters

The correlation chart (Fig. 28) illustrates the positive correlation ($r = 0.769$) of the objective of minimizing final energy with the south window to wall ratio. The south facade receives higher solar heat gains so 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, solar heat gains are reduced, more wall area helps retain the existing indoor thermal comfort through more insulation and smaller openings that result to reduced natural ventilation rate, thus reduced heat transfer. The charts (Figs. 26 and 27) created with the sensitivity analysis tool of modeFRONTIER show that the window to wall ratio of all the facade orientations are more influential than the shading area optimization both for the final energy and thermal comfort objectives.

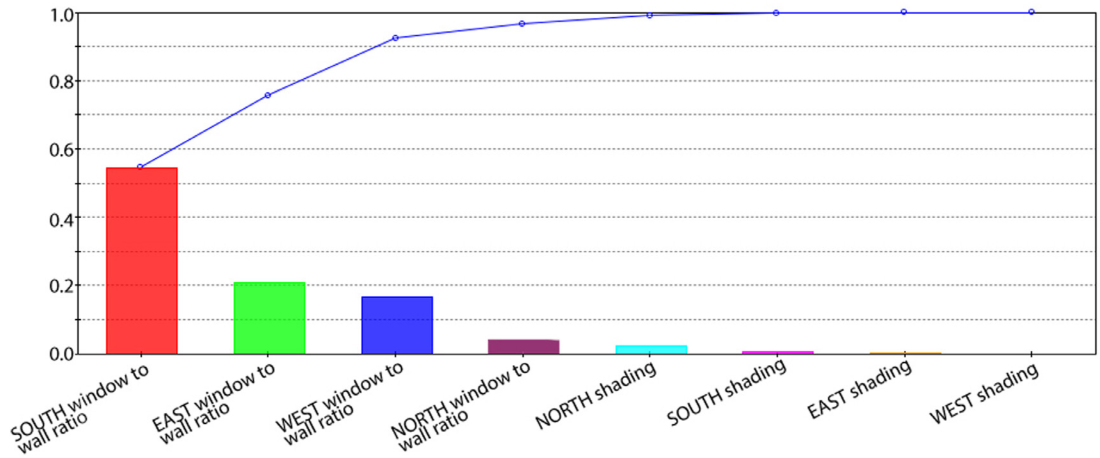

Fig. 26. Effect of variables on minimizing energy demand.

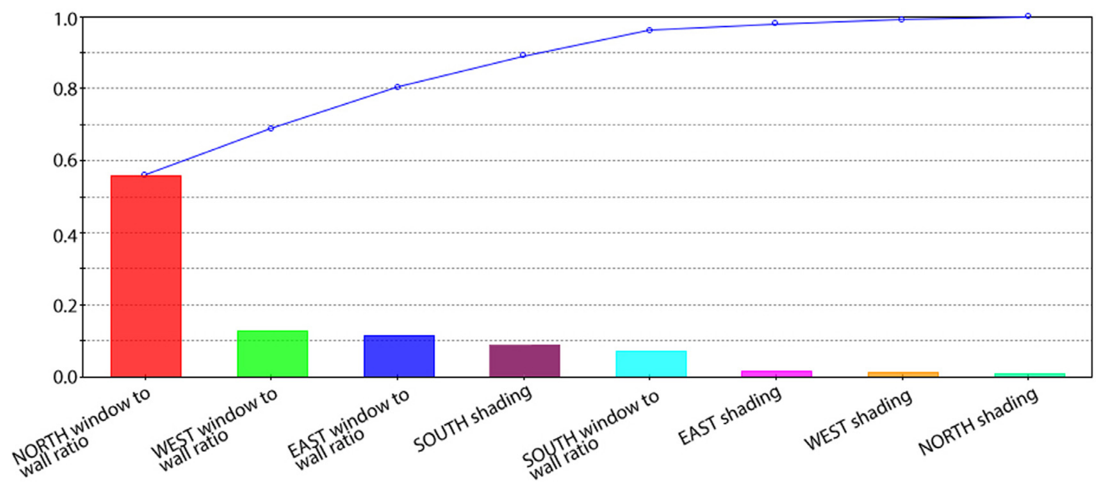

Fig. 27. Effect of variables on maximizing comfort.

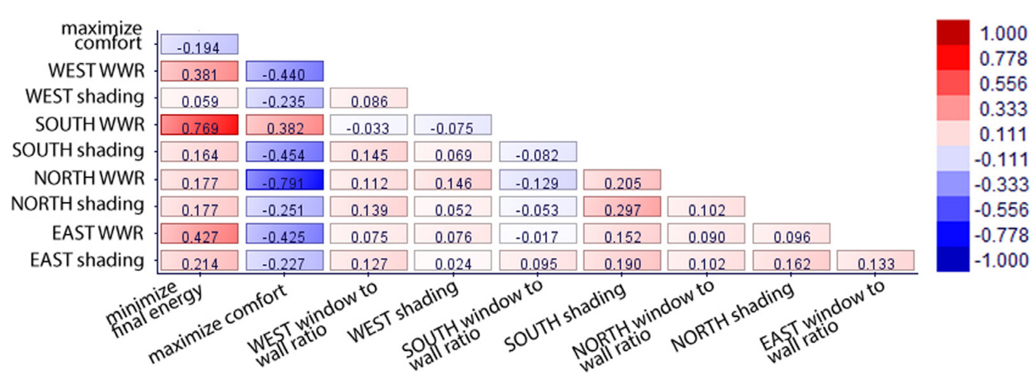

Fig. 28. Pearson correlation chart.

5. Conclusion

By applying the integrated strategy for the Mediterranean climate of Athens, it was possible to assess the effects of the envelope, HVAC and energy generation parameters on a central core, high-rise office building. Energy simulations were driven by an optimization strategy and derived data were analysed by sensitivity analysis that indicated the parameters with higher impact on annual energy demand, energy production and adaptive thermal comfort levels. These parameters are: cooling set-point, natural ventilation strategies, glazing g-value, window-to-wall ratio and energy production with PV panels. By applying the proposed integrated strategy, the building's energy performance is reduced by 33% (from 109.12 kWh/(m^2a) to 73.13 kWh/(m^2a)) and the comfort hours are increased by 18.2% (from 78.3% to 96.5%), from the starting point of the current regulations in Greece [18]. The starting building refers to: window to wall ratio = 40%/ wall U-value = 0.5 W/m^2K / glazing U-value = 2 W/m^2K / glazing g-value = 0.5/ infiltration = 0.2ach/ cooling-set-point = 26 °C. The final optimal design depicted in Fig. 25, has an annual final energy of 73.13 kWh/(m^2a) and is comfortable for the 96.49% of time in an annual period, when the office spaces are occupied.

An extensive number of simulations driven by an optimization algorithm was needed in order to investigate the impact of various design variables on final energy and thermal comfort. The results of this study indicate the following:

- The measures that need to be taken in the early-phase of designing a nZEB central core, open plan, office building in a Csa (Köppen–Geiger) Mediterranean climate and derive from the optimal building design of this research are: window to wall ratio = 20% for all facade orientations/ shading area of openings = 25% for all facade orientations/ wall U-value = 0.1 W/m^2K/glazing U-value = 1.8 W/m^2K/glazing g-value = 0.3/infiltration = 0.1 ach/cooling-set-point = 26 °C.
- The parameters with the highest impact on the objectives of this research are the cooling set-point, natural ventilation strategies, the glazing g value, the window-to-wall ratio and energy production with PV panels on the facades of the building.
- The parameters with lower impact on the objectives of this research are the wall U-value, the glazing U-value, the infiltration rate, shading systems of the openings, floor plan shape and orientation of the building.
- For the climatic conditions of Athens, adaptive design of the facade openings per orientation and adaptive shading area per orientation will not lead to significantly reduced energy loads in the presence of smaller openings and energy production systems on the facade.
- The presence of active systems has influenced passive design optimizations.
- The integrated optimization of window to wall ratio, energy generation on the facades and shading area has overshadowed the effects of adaptive shading area per orientation.
- For cooling dominant climates with outdoor temperatures within the range of indoor comfort for a large part of the year, adopting natural ventilation strategies in combination with BMS (building management systems) has a high potential towards designing a zero energy high-rise building.
- Generating electricity from PV panels on the facades of high-rise buildings can also greatly reduce their energy consumption in climates similar to Athens, Greece.
- The proposed integrated strategy of conflicting passive and active systems and its computational set-up are generic and can be applied to various building typologies and climatic zones.
- The proposed integrated strategy that is driven by algorithm aided multi-objective optimizations, contrary to existing stepped strategies, can enable the designer to attain substantial information, in a time-efficient manner, through data analysis of large number of different building designs. These data can help the designer to comprehend the impact of conflicting design parameters regarding the energy and thermal comfort performance of a building.

The derived design measures stem from a building with no surrounding buildings. Taking into consideration a dense urban environment could leave more room for adaptive design, but would demand more accurate and time consuming models and simulations. Simulation time could also drastically increase by including more detailed systems and parameters in the optimization procedure. This study focused on examining parameters related to early decision making phase of designing a high-rise office building. Possible next steps could exploit the results from this decision making step and perform further optimizations on more detailed and adaptive design of the parameters with higher potential for improvement. This gradual optimization approach would be beneficial for taking informed design decisions in a time-efficient manner, towards the transition from early decision-making concepts to detailed execution.

Author declaration

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from *Energy and Buildings*.

References

[1] Active House Alliance, in: ACTIVE HOUSE - the guidelines, Active House, Bruxelles, 2015, pp. 8–62.
[2] U. Berardi, A cross-country comparison of the building energy consumptions and their trends, Resour. Conserv. Recycl. 123 (2017) 230–241.
[3] L. Caldas, Generation of energy-efficient architecture solutions applying GENE_ARCH: an evolution-based generative design system, Adv. Eng. Inform. 22 (1) (2008) 59–70.
[4] F. Chantrelle, H. Lahmidi, W. Keilholz, M. Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Appl. Energy 88 (4) (2011) 1386–1394.
[5] Energyplus.net. (2017). Weather Data by Location, EnergyPlus. [Online] Available at: https://energyplus.net/weather
[6] R. Evins, P. Pointer, S. Burgess, Multi-objective optimisation of a modular building for different climate types, in: Proceedings of the First Building Simulation and Optimization Conference, UK, 2012, pp. 173–180.
[7] D. Founda, Evolution of the air temperature in Athens and evidence of climatic change: a review, Adv. Build. Energy Res. 5 (1) (2011) 7–41.
[8] E.D. Giouri, Zero Energy Potential of a High Rise office Building in a Mediterranean Climate M.Sc. thesis., Delft University of Technology, 2017.
[9] M. Hamdy, A. Hasan, K. Siren, A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy Build. 56 (2013) 189–203.
[10] J. Holst, Using whole building simulation models and optimizing procedures to optimize building envelope design with respect to energy consumption and indoor environment, in: Proceedings of the Eighth International IBPSA Conference, the Netherlands, 2003, pp. 507–514.
[11] T. Konstantinou, Facade Refurbishment Toolbox, Supporting the Design of Residential Energy Upgrades Ph. D Thesis., Delft University of Technology, 2014.
[12] Lianopoulos, M. (2010). [Online] Greekarchitects.gr. Available: http://greekarchitects.gr/competition2010 [Accessed 2012]
[13] R. Looman, Climate-Responsive Design, A Framework for an Energy Concept Design-Decision Support Tool for Architects Using Principles of Climate-Responsive Design Ph.D. Thesis., Delft University of Technology, 2017.
[14] R. Loonen, M. Trka, J.L.M. Hensen, Exploring the potential of climate adaptive building shells., in: Proceedings of the 12th International Building Performance Simulation Association Conference, Sydney, 2011, pp. 2148–2155.
[15] E.H. Lysen, The Trias Energica: solar energy strategies for developing countries, in: Proceedings of the Eurosun Conference, Freiburg, 1996, pp. 1–6. September 16-19.
[16] V. Machairas, A. Tsangrassoulis, K. Axarli, Algorithms for optimization of building design: a review, Renew. Sustain. Energy Rev. 31 (2014) 101–112.
[17] M. Manzan, Genetic optimization of external fixed shading devices, Energy Build. 72 (2014) 431–440.
[18] Ministry of Environment Energy and Climatic Change, in: Detailed National Standards of Parameters for the Calculation of Energy Building Performance and Issuing of Certificates of Building Performance, Technical Chamber of Greece, Athens, 2012, pp. 20–143.

[19] K. Negendahl, T. Nielsen, Building energy optimization in the early design stages: a simplified method, Energy Build. 105 (2015) 88–99.
[20] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (6) (2002) 563–572.
[21] R. Pfluger, in: Simulation Des Thermischen Gebäudeverhaltens eines Passivhauses in Geschoßwohnungsbau- Typologie und Städtischer Bebauung, PHI Passivhaus-Institut, Darmstadt, 2007, pp. 3–31.
[22] R. Pfluger, W. Feist, S. Ludwig, J. Otte, in: Nutzerhandbuch Für Den Geschoßwohungsbau in Passivhaus-Standard, German Federal Office for Building and Regional Planning, 2007, p. 11. [ebook].
[23] M.S. Roudsari, M. Pak, A. Smith, Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design, in: Proceedings of the 13th international IBPSA conference, Lyon, France, 2013, pp. 3128–3135. August.
[24] X. Shi, Design optimization of insulation usage and space conditioning load using energy simulation and genetic algorithm, Energy 36 (3) (2011) 1659–1667.
[25] M. Taleghani, M. Tenpierik, S. Kurvers, A. van den Dobbelsteen, A review into thermal comfort in buildings, Renew. Sustain. Energy Rev. 26 (2013) 201–215.
[26] T. Tusar, B. Filipic, Visualization of Pareto front approximations in evolutionary multiobjective optimization: a critical review and the prosection method, IEEE Trans. Evol. Comput. 19 (2) (2015) 225–245.
[27] United Nations, Department of Economic and Social Affairs, in: World Urbanization Prospects. The 2014 Revision Highlights, United Nations, New York, 2014, pp. 7–10.
[28] A.A.J.F. Van den Dobbelsteen, Towards closed cycles - New strategy steps inspired by the Cradle to Cradle approach, in: Proceedings of the 25th Conference on Passive and Low Energy Architecture, Dublin, 2008, pp. 1–6. 22–24 October.
[29] J. Xu, J. Kim, H. Hong, J. Koo, A systematic approach for energy efficient building design factors optimization, Energy Build. 89 (2015) 87–96.
[30] D. Yang, S. Ren, M. Turrin, S. Sariyildiz, Y. Sun, Multi-disciplinary and multi-objective optimization problem re-formulation in computational design exploration: a case of conceptual sports building design, Autom. Constr. 92 (2018) 242–269.
[31] W. Yu, B. Li, H. Jia, M. Zhang, D. Wang, Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design, Energy Build. 88 (2015) 135–143.