16

Energy design of building shape and envelope

It is now generally accepted that end cost, energy efficiency and general performance of buildings are strongly determined in the early stages of design (Miles et al. 2001, Wang et al. 2006, Turrin et al. 2011). It is therefore necessary for designers to be able to gather pertinent building performance information in this stage of the design process.

In order for designers to gather pertinent information for the early stages of design, a good comprehension of this phase is necessary. In this phase, design decisions have consequences for different aspects of the building, for example, structural integrity, indoor environmental quality, energy efficiency and costs. Many of these aspects are often in contrast with one another. A good example of these contrasts is natural illumination vs. solar shading in warm climates. Pertinent information in the early phase of design therefore needs to include multiple disciplines and deal with contrasting objectives.

A buildings general shape, fenestration, orientation and implantation on the building site are some of the first and most critical decisions made by architects in the design process. They have far reaching consequences and should be taken with a great many variables in mind. Most importantly for this work, a buildings shape, orientation and fenestration will greatly determine its exposure to the sun, and therefore have a great incidence in its indoor environmental quality and energy efficiency.

The building envelope is perhaps one of the most interesting subjects when we think about multidisciplinary design. Envelopes are responsible for most of the building's exposure to the elements, carrying with this a good part of the responsibility for indoor environmental quality and energy efficiency. Envelopes are also regularly an important component it the buildings structure and are big part of their budget.

The energy related applications in this PhD thesis use search algorithms and parametric models to study the shape, orientation and envelope of an office building, in order to generate energy efficient solutions and information that will help designers make sound decisions in the early stages of design.

Fanger defines thermal comfort as a state of mind in which occupants desire no modifications to the air temperature of a room (Fanger 1970). Moreover, when humans are in an optimal temperature range, they do not need the use of their body's thermal control systems, they do not sweat or shiver. The thermal sensation we perceive is most importantly determined by six factors: Air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing. Out of these six factors metabolic rate and clothing do not depend on the building environment, but on the person. Air temperature, mean radiant temperature, air velocity and humidity depend greatly on external conditions, but also on building characteristics (Attia 2012).

Most countries have legislation and building codes that require fixed indoor air temperature ranges and relative humidity in order to guarantee the thermal comfort of their occupants. As previously mentioned, external conditions play a great role in these indoor characteristics, is therefore not always possible to maintain comfort ranges with the use of only passive building design. It is often the case in very common and populated climates to use indoor climate control systems such as air conditioning, heat radiators and humidity control systems. These systems consume a great deal of energy, and this consumption can be greatly reduced by efficient building design. In Italy, 45% of the total national energy consumption is due to building energy consumption, 83% of which is due to energy consumption during the buildings operation, the rest to their construction (Corrado & Paduos 2010).

In order to increase the energy efficiency of new buildings, we need to have accurate models of calculation the buildings future energy needs with a great deal of sensitivity on the buildings features. In this chapter we present the models used for the energy requirements calculations for heating, cooling and lighting of internal spaces.

16.1 Total Energy Requirements

The total energy requirements of a building's heating and cooling system can be summed up in the following equation:

$$Q_{tot} = Q_{H,nd} \cdot 1/e_H + Q_{C,nd} \cdot 1/e_C + Q_{E,nd} \cdot 1/e_E \qquad (16.1)$$

where Q_{tot} is the total energy requirements for heating and cooling, $Q_{H,nd}$, $Q_{C,nd}$ and $Q_{E,nd}$ are the ideal energy requirement for heating, cooling and electricity respectively, and e_H, e_C and e_H are efficiency coefficient related to the heating, cooling electricity systems respectively.

Ideal energy refers to the amount of energy that is effectively needed to guarantee a given air temperature or a given luminance value. It is called ideal because it does not take into account the energy losses incurred from the primary energy source to the emission of this energy in the indoor environment. All building energy systems have energy losses in their procedures. Losses can be related to energy generation, distribution or emission. A perfect system would be one that emits the same amount of energy as the amount of primary energy it receivers.

This PhD thesis regards only the design of the building, this work does not consider building energy generation, distribution and emission systems, nor their efficiency in different building types. Therefore in this work we will only discuss ideal energy, the amount of energy required to achieve indoor environmental goals, mainly $Q_{H,nd}$, $Q_{C,nd}$ and $Q_{E,nd}$. We can thus rewrite the total energy requirement equation as follows:

$$Q_{tot} = Q_{H,nd} + Q_{C,nd} + Q_{E,nd} \qquad (16.2)$$

16.2 Heating and Cooling Requirements calculation

The calculation of the required heating loads for any particular space involves many variables, and it is therefore a complex endeavor. Perhaps most significantly it involves the time factor, as the transmission of heat is subject to many time-related issues, such as thermal conduction, accumulation and release in building materials with big masses. Computational simulations of the heating and cooling loads are increasingly becoming of standard use in architectural practices. They have been incorporated into many commercial CAD applications, either directly (as in the case of Autodesk Revit) or by means of plugins (as in the case of the Open Studio plugin for SketchUp). Attia and De Herde provide a review of 10 building energy performance tools in (Attia & De Herde 2011).

Among these computational energy calculation applications, Energy Plus has been signaled out by researchers for its accuracy (Attia & De Herde 2011). Energy plus is an application developed by the department of energy of the U.S. and is freely available.

> "EnergyPlus is an energy analysis and thermal load simulation program. Based on a users description of a building from the perspective of the buildings physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points."

(US Department of Energy 2013)

The Energy plus documentation lists among the many capabilities of the software:

- Sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones.
- Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step.
- Transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions.

Figure 16.1 shows a diagram of the simulation method employed by energy plus. In it we can see how each thermal zone is studied. Thermal zones are subdivisions of the building model that should reflect not the internal partition of the building, but the thermal subdivisions of the building. Adjacent areas that are climatized at the same temperature should be added into a single thermal zone. Areas that are climatized at different temperatures or not climatized should be modeled as separate thermal zones.

The Air Heat Balance is calculated by a system of equations in which the unknowns are the superficial temperatures of all of the internal surfaces in each zone and the zone's air temperature. Several assumptions are made in this calculation: Air and surface temperatures are perfectly uniform, surfaces are perfectly diffusive and internal air is transparent to thermal and solar radiation. The Air Heat Balance determines the heating and cooling loads for each thermal zone and, in turn, the entire building.

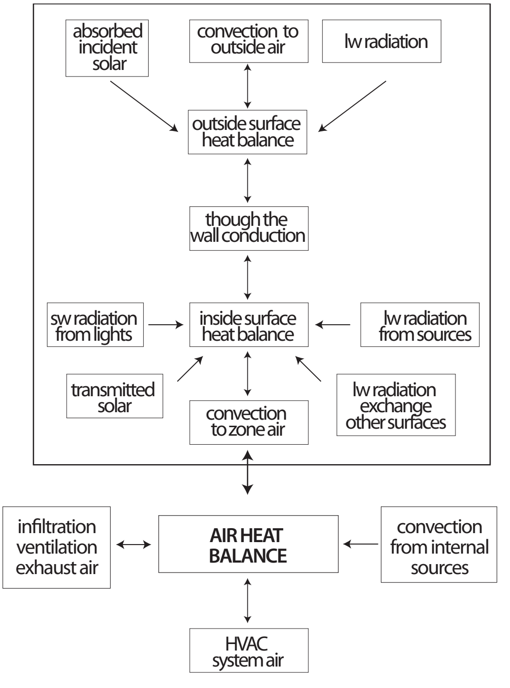


Figure 16.1: Energy Plus simulator diagram - Image taken from the software documentation.

In order for energy plus to calculate thermal loads, the building has to be described adequately. Buildings are described in three main areas:

- Their physical characteristics (geometry, construction, materials, orientation, etc.).
- Their HVAC system characteristics.
- Their functional characteristics (occupation hours, people activity level, internal electric equipment, etc.).

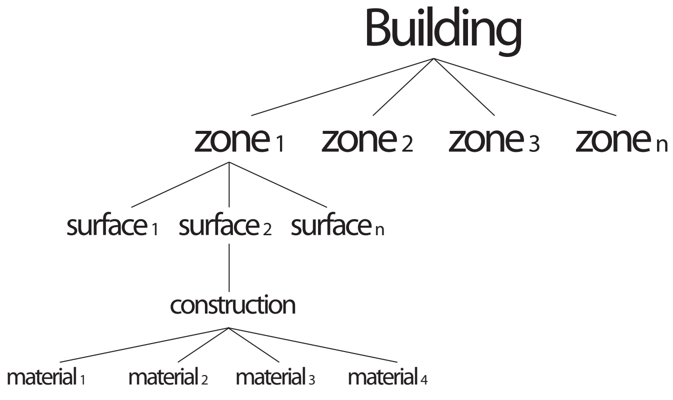


Figure 16.2: Energy Plus Building description diagram.

Figure 16.2 shows a diagram of the characterization of building components in energy plus (as well as the majority of energy simulations software). As previously mentioned, the building is subdivided into several thermal zones. Each zone is described in terms of its geometry, volume and internal surfaces. Each internal surface of the zone is in turn described in its adjacency to other thermal zones or to the external environment, and its construction; the way the surface is materially composed. Surfaces in a zone can include internal and external walls, ceilings, floors, doors or windows. External surfaces can also be described, such as external shading devices or other buildings. The surface construction is determined by a stratigraphy of materials. Each material also has to be defined, its thickness (s), conductivity (λ), density (ρ) and specific heat (c_p) values are all selected.

The HVAC systems are described in terms of their winter and summer temperature set points, function calendar (time of day and days of the week in which it functions).

Functional characteristics of the building include the number of persons per unit area, their activity level, generation of carbon dioxide, etc. Electrical equipment is also described for each zone, in therms of their energy consumption in (W/m^2) and their radiation.

The other important factor to describe for computational energy simulation is the outdoors climate conditions. This is done via a “weather file” that contains external air temperatures, solar radiation and wind conditions for the entire year.

16.3 Lighting Energy Requirements

There are many computational methods for determining the quantity, quality and distribution of natural light in spaces, depending on desired luminance levels, internal surfaces and external conditions. This kind of calculation can then be used to determine the level of visual comfort of the building occupants. This kind of analysis is not included in this work, the present PhD thesis is interested in the energy requirements of lighting fixtures for internal spaces. Therefore, the object of this section is to describe how energy simulation software can determine illuminance levels in a few indoor reference points, and the amount of electrical energy required to compensate when natural light is not enough to meet a given level. Energy plus was also employed for this analysis.

> "The EnergyPlus daylighting model, in conjunction with the thermal analysis, determines the energy impact of daylighting strategies based on analysis of daylight availability, site conditions, window management in response to solar gain and glare, and various lighting control strategies."

(US Department of Energy 2013)

The documentation provided with energy plus describes three main steps in the daylighting calculation:

> ◦ "Daylight factors, which are ratios of interior illuminance or luminance to exterior horizontal illuminance, are calculated and stored. The user specifies the coordinates of one or two reference points in each daylit zone. EnergyPlus then integrates over the area of each exterior window in the zone to obtain the contribution of direct light from the window to the illuminance at the reference points, and the contribution of light that reflects from the walls, floor and ceiling before reaching the reference points. Window luminance and window background luminance, which are used to determine glare, are also calculated. Taken into account are such factors as sky luminance distribution, window size and orientation, glazing transmittance,

inside surface reflectances, sun control devices such as movable window shades, and external obstructions. Dividing daylight illuminance or luminance by exterior illuminance yields daylight factors. These factors are calculated for the hourly sun positions on sun-paths for representative days of the run period. To avoid the spikes of daylight and glare factors calculated during some sunrise and/or sunset hours when exterior horizontal illuminance is very low, the daylight and glare factors for those hours are reset to 0."

- "A daylighting calculation is performed each heat-balance time step when the sun is up. In this calculation the illuminance at the reference points in each zone is found by interpolating the stored daylight factors using the current time steps sun position and sky condition, then multiplying by the exterior horizontal illuminance. If glare control has been specified, the program will automatically deploy window shading, if available, to decrease glare below a specified comfort level. A similar option uses window shades to automatically control solar gain."
- "The electric lighting control system is simulated to determine the lighting energy needed to make up the difference between the daylighting illuminance level and the design illuminance. Finally, the zone lighting electric reduction factor is passed to the thermal calculation, which uses this factor to reduce the heat gain from lights."

(US Department of Energy 2013)

In order for energy plus to calculate the electric energy requirements for the artificial illumination of internal spaces, additional input is required. All of the geometrical and material considerations described above (like glass material properties) are considered in the daylighting calculation, but additionally, illuminance set-points in lux need to be specified for each zone reference point. Coordinates of the reference points, as well as their relative importance in the zone are also specified.

16.4 Climate Zones

> "Although now over 100 years old, the classification of climate originally formulated by Wladimir Köppen and modified by his collaborators and successors, is still in widespread use. It is widely used in teaching school and undergraduate courses on climate. It is also still in regular use by researchers across a range of disciplines as a basis for climatic regionalization of variables and for assessing the output of global climate models."

(Peel et al. 2007)

The Köppen - Geiger climate classification system is used in this PhD research to identify the most prominent climates in Europe. It is an attempt to select 4 climates that will represent the vast majority of the european continent that will then be used to study energy efficient buildings through multi-objective search algorithms. Table 16.1 shows the classification system, how it divides climates and the criteria for them to appertain to all categories.

Figure 16.3 shows the Köppen - Geiger climate map of europe. By looking at it we can see that the vast majority of the continents surface is covered by C and D climate types. Southernmost regions of Europe are described as Csa, Cfb and Cfa climates cover most of the mid-latitude European regions, and many of the most northern and eastern regions are described as Dfb climates.

For this PhD research, four cities were chosen to represent these climates. The Italian city of Plalermo is selected as a Temperate dry-hot summer (Csa), Torino in northern Italy is chosen as a Temperate wet-hot summer (Cfa), Frankfurt Germany as a Temperate wet-warm summer (Cfb) and Oslo Norway as a Cold wet-warm summer (Dfb). Figure 16.4 shows Tregenza Sky domes for all cities, showing solar radiation directions and energy in kWh/m^2. Table 16.2 shows the average monthly dry bulb temperatures (C°) in these locations.

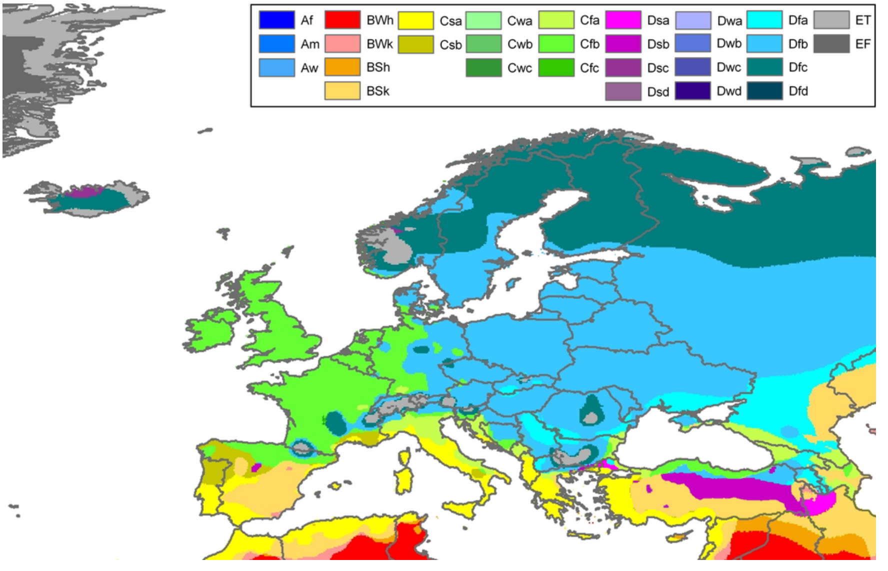


Figure 16.3: Köppen - Geiger Climate type map of Europe.

Table 16.1: Description of Köppen - Geiger climate symbols and defining criteria - Taken from (Peel et al. 2007).

1_{st}	2_{nd}	3_{rd}	Description	Criteria
A			**Tropical**	$T_{cold} \geq 18°$
	f		-Rainforest	$P_{dry} \geq 60°$
	m		-Monsoon	Not(A_f) & $P_{dry} \geq$ 100-MAP/25
	w		-Savannah	Not(A_f) & $P_{dry} <$ 100-MAP/25
B			**Arid**	MAP $< 10\times P_{threshold}$
	W		-Desert	MAP $< 5 \times P_{threshold}$
	S		-Steppe	MAP $\geq 5 \times P_{threshold}$
		h	-Hot	MAT $\geq 18°$
		k	-Cold	MAT $< 18°$
C			**Temperate**	$T_{hot} > 10°$& $0 < T_{cold} < 18°$
	s		-Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		-Dry Winter	$P_{wdry} < P_{swet}/10$
	f		-Without dry season	Not (C_s) or (C_w)
		a	-Hot Summer	$T_{hot} \geq 22°$
		b	-Warm Summer	Not (a) & $T_{mon10} \geq 4°$
		c	-Cold Summer	Not (a or b) & $T_{mon10} < 4°$
D			**Cold**	$T_{hot} > 10°$& $T_{cold} \leq 0°$
	s		-Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		-Dry Winter	$P_{wdry} < P_{swet}/10$
	f		-Without dry season	Not (D_s) or (D_w)
		a	-Hot Summer	$T_{hot} \geq 22°$
		b	-Warm Summer	Not (a) & $T_{mon10} \geq 4°$
		c	-Cold Summer	Not (a, b or d)
		d	-Very Cold Winter	Not (a or b) & $T_{cold} <$ -38°
E			**Polar**	$T_{hot} < 10°$
	T		-Tundra	$T_{hot} > 0$
	F		-Frost	$T_{hot} \leq 0$

MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

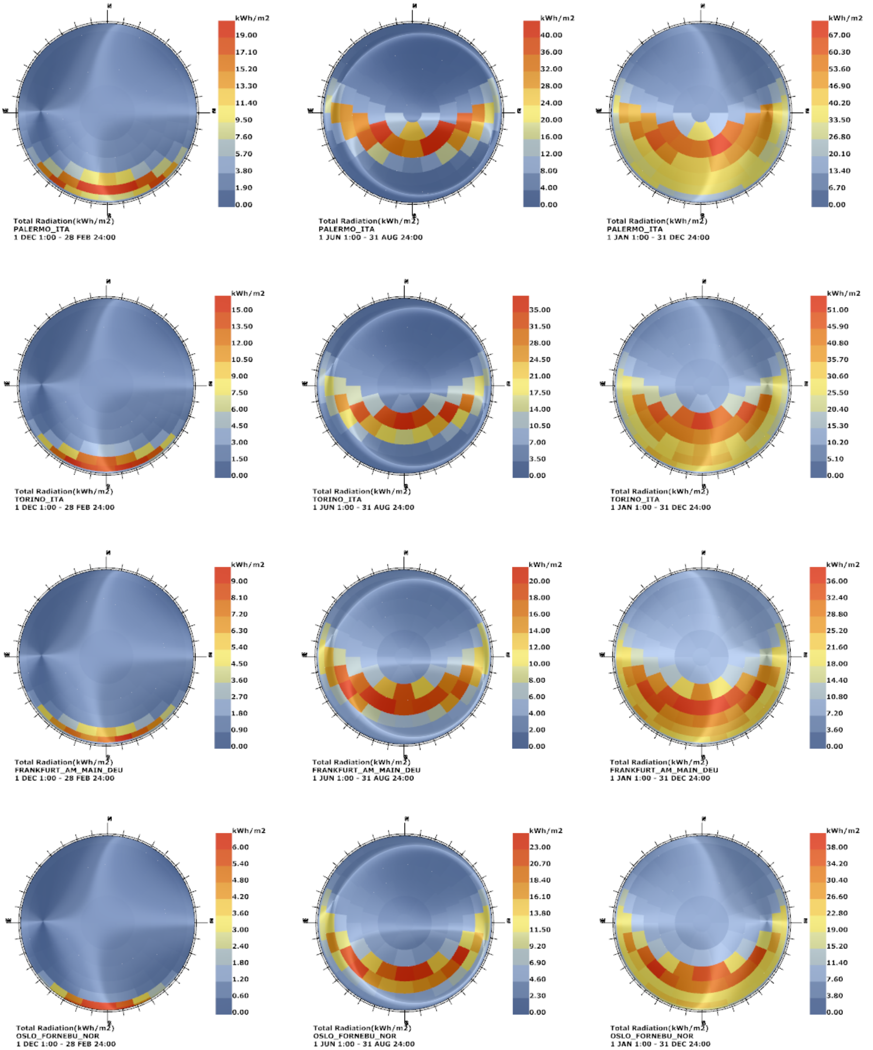


Figure 16.4: Solar radiation Tregenza Sky Dome diagrams in winter, summer and whole year for Palermo, Torino, Frankfurt and Oslo

Table 16.2: Average monthly dry bulb temperature (C°) for Palermo, Torino, Frankfurt and Oslo.

Month	Palermo	Torino	Frankfurt	Oslo
Jan	12.6	1.8	2.3	-3.7
Feb	11.8	3.8	1.7	-0.8
Mar	13.8	8.1	5.5	0.9
Apr	15.6	11.8	9.2	4.6
May	19.1	16.0	14.7	11.9
Jun	22.8	19.5	16.4	14.7
Jul	25.5	23.0	19.5	17.5
Aug	27.0	21.9	18.6	16.5
Sep	24.1	18.1	14.9	11.0
Oct	21.6	12.3	10.6	6.7
Nov	17.2	6.3	4.7	1.7
Dec	13.9	2.6	1.7	-1.6

17

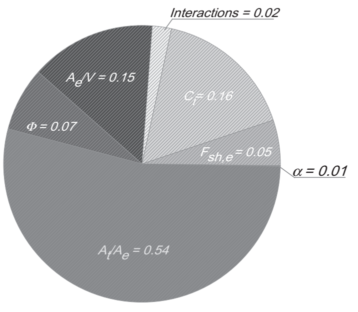
The Building Shape and Orientation

Mechri et al. (Mechri et al. 2010) performed a sensitivity analysis with the objective to determine the building variables that have the biggest incidence in heating and cooling energy needs in several italian climates. The variables they studied were the compactness ratio (Area of the envelope to volume ratio (A_e/V), envelope transparent to opaque ratio(A_t/A_e), absorptance or external color (α), building orientation (Φ), external shading ($F_{sh,e}$) and internal effective heat capacity (C_i). Figure 17.1 shows the decomposition of the total variance of the energy needs for heating and cooling for Palermo and Cuneo. The study found that the variable that had by far the most influence in the energy requirements was the transparent to opaque envelope ratio (A_t/A_e) both in cooling and heating and in all climates. Envelope to volume ratio (A_e/V) and internal heat capacity (C_i) are also influential in a lesser degree. Surprisingly building orientation did not have a big influence for the orientation ranges studied by Mechri et al.

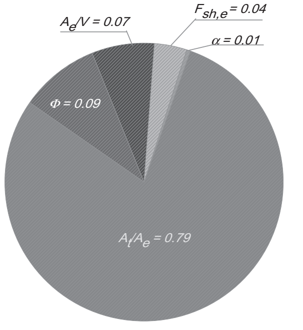
If we look at these variables in terms of early design stage, A_e/V, A_t/A_e and Φ are some of the first decisions to be made in the design process. A_e/V can be defined as the building shape since perimeter to area ratios vary with plan shape. A_t/A_e is the combination of the building shape and the overall fenestration scheme. Building orientation in most cases is very much related to the building site, but in the cases where sites allow for different implantations, this is commonly defined in the early stages as well.

This PhD thesis looks into these early stage design variables in energy efficiency. In this chapter the building shape and orientation are studied.

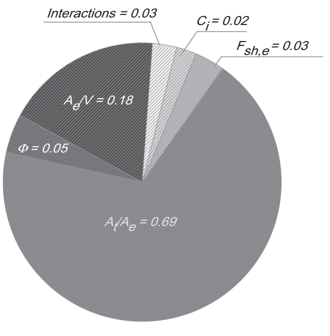
Kämph and Robinson studied the overall shape of the building in an urban context by means of evolutionary algorithm, looking to maximize solar



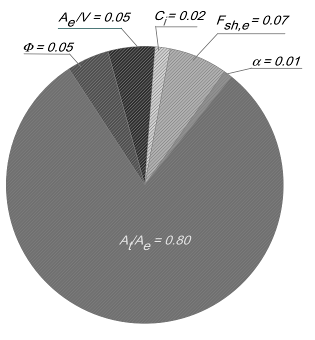
(a) Decomposition of the total variance of the heating energy needs for Palermo.



(b) Decomposition of the total variance of the cooling energy needs for Palermo.



(c) Decomposition of the total variance of the heating energy needs for Cuneo.



(d) Decomposition of the total variance of the cooling energy needs for Cuneo.

Figure 17.1: Decomposition of the total variance of the energy needs for cooling and heating for Cuneo and Palermo (Mechri et al. 2010).

irradiation (Kämpf & Robinson 2010). They investigated 3 different parametric models of different shapes and found "non-intuitive" geometries that had up to 20% increase in solar gains when compared to more traditional shapes.

Wang et al. studied the polygonal plan shape of a building by means of multi-objective genetic algorithm, with the purpose to minimize Life Cycle Costs (LCC) and Life Cycle Environmental Impact (LCEI) (Wang et al. 2006). These two contrasting functions were found to be well influenced by the shape of the polygonal building. Buildings that had low LCC values had more regular polygonal shapes, while LCEI low values were found when buildings had longer south-facing facades.

17.1 Case Study 8: Building Shape and Orientation

Case study 8 describes the use of multi-objective search algorithms to determine energy efficient rectangular building proportions and orientations. Buildings in this case study will be studied in terms of their heating, cooling and lighting energy needs for 4 european climates. Palermo, Torino, Frankfurt and Oslo were chosen to represent a high percentage of all of the climates present in the european continent.

The objective of this case study is to determine optimal orientation and building width/length ratios (w/l). The search process will examine combinations of orientations and (w/l) to minimize building energy consumption. Since only orientation and (w/l) are being examined, all other parameters will be kept fixed, most importantly, the A_t/A_e ratio. Masonry building envelopes are studied in this PhD thesis. As was the case for the structural case study, brick facades and their openings are the objective of this series of energy efficiency search process. In this case however, these values will be kept fixed. A fixed A_t/A_e value of 45 % is used, and a fixed 50cm thickness is used for all orientations.

The are no external shading devises, but the building envelope thickness itself is used as a shading surface, since windows are position at the internal edge of the envelope. We can make an analogy with traditional external shading devices, the lateral surfaces of the wall opening can be considered as shading fins, and the superior surfaces as an overhang.

17.1.1 Case Study Building

Energy requirements are studied in a case study building, or more accurately, on one of the building's floors. The building has the same characteristics of the building described in chapter 11. It is a 6 story high office building with a rectangular plan. The floor studied is a standard floor just above the ground floor. The floor has a fixed area of 280 m^2 and a height of 4m.

The building floor that is being studied is modeled by means of a singe thermal zone. In order to properly model the building as an office building, the following functional characteristics were given to Energy Plus:

- People activity level: 13.8 W/m^2
- Electric equipment: 6.454 W/m^2
- The ventilation rate was set to 1.7 air changes per hour during weekdays from 8.00 AM to 9.00 PM and to 0.25 h^{-1} during the rest of the day and during weekends.
- The heating and cooling set point temperatures were respectively set to 20 °C and 26 °C. The systems were active from 7.00 AM to 9.00 PM during weekdays only.
- Lighting control was performed with two control points and dimmed control option. For glare control, the occupants' seats were placed facing north. The maximum lighting level was set to 10 W/m^2 per zone floor area. The lighting schedule was set equal to the occupancy one.
- The solar absorption coefficient of the external opaque surfaces was set to 0.6, which corresponds to a medium color.

The occupancy schedule of the building during weekdays is shown in figure 17.2. The building was assumed to be unoccupied during the weekends.

17.1.2 Building envelope materials

We previously mentioned the way in which the building to be studied is detailed for Energy Plus, its materials, constructions and thermal characteristics. The materials and constructions used in case study presented in this chapter are described bellow.

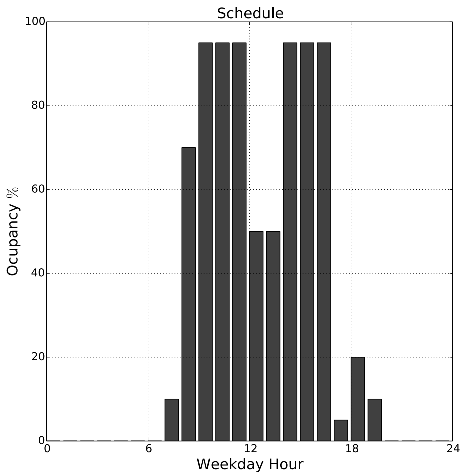


Figure 17.2: Office building occupancy schedule for weekdays.

Windows

Since case study 8 focuses on building orientation and proportions, window materials are kept fixed. There is one single window construction given to Energy plus to describe the windows. The construction used in described in the following table:

Composition mm	Position low-e coating	U_g $W/(m^2K)$	g_g -	τ_1 -
4glass; 12air ; 4glass	-	2.68	0.77	0.81

A double glazed window construction is used, with 4mm glasses and a 12 mm air gap.

Walls and Slabs

Wall constructions for case study 8 are the same for all orientations. Ceiling and floor slabs are modeled as adiabatic surfaces in order to consider only the building envelope as a design variable. They are however described in constructions on their own in order to consider their influence on the study floor. Wall and slab materials and constructions for case study 8 are described in tables 17.1 and 17.2 respectively. EPS thickness was explicitly calculated to achieve a U-value of 0.33 W/(m^{2}K).

The floor of the office building in this case study is an open space plan. This choice was made to place greater emphasis on the building envelope. There are no other internal surfaces that can create shaded areas or add internal mass to the space.

Table 17.1: Characteristics of materials for case study 8.

Material	s m	λ W/(mK)	ρ kg/m^3	c_p J/(kgK)
External gypsum	0.02	0.9	1800	840
EPS	0.07	0.031	112.1	1450
Bricks	0.5	0.5	1600	840
Internal gypsum	0.01	0.7	1400	840
Floor slab	0.25	0.678	1280	1000
Floor tiles	0.02	2.69	2700	984
Air gap	0.13	R:	0.18	m^{2}K/W

Table 17.2: Wall and slab Constructions for case study 8.

Component	Layer 1	Layer 2	Layer 3	Layer 4
Masonry wall	External gypsum	EPS	Bricks	Internal gypsum
Floor	Internal gypsum	Floor slab	Air gap	Floor tiles
Ceiling	Floor tiles	Air gap	Floor slab	Internal gypsum

17.1.3 Parametric Model

The parametric model used for case study 8 has only two variables. The first variable x_1 refers to the buildings width (w). The building's length is calculates from its width and the fixed floor area A_p of 280 m^2. Following this logic, all possible solutions have the same floor area A_p and the same internal volume. Hence, these two dimensions do not influence the results of the search process in any way. In this sense length is also varies during the search process, but it is determined as $l = A_p/w$.

The second variable x_2 is the angle of rotation that determines the buildings orientation. The building is allowed to rotate 45°in a clockwise direction and 45°in a counterclockwise direction. The parametric model for case study 8 is shown in figure 17.3.

It is important to notice that the 50 cm masonry walls create shading overhangs and fins on the windows that are on the inside of the wall. Since these windows are long and not very high, the overhangs are in a better position to shade the windows, especially during the summer moths.

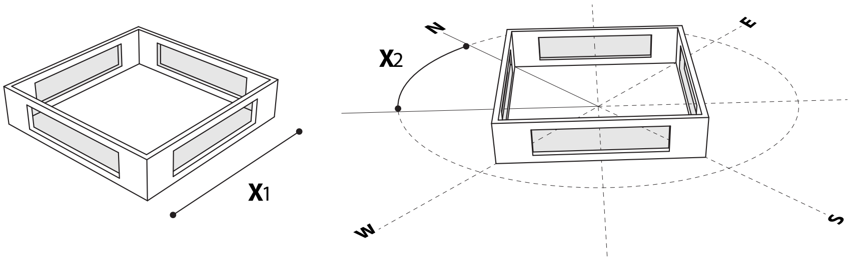


Figure 17.3: Parametric Model for Case Study 8.

17.1.4 Fitness functions

Case study 8 is a search process for energy efficiency considering heating, cooling and lighting (electric) energy requirements. It can be argued that in the end these energy requirements will all be translated into one single energy requirement value, much in the way that is shown in equation 16.2. However, these energy values would have to be calculated in terms of primary energy in order to be added together. Heating and cooling needs are estimated in therms of thermal loads, while lighting energy needs are calculated as electric energy, hence they cannot be added as they are. We would need to calculate them in terms of primary energy, taking into account the influence of the heating, cooling and lighting systems.

Different systems would produce different results in calculating primary energy. Thus, selecting an energy system for our case study would greatly influence the envelopes studied during the search process. Energy systems are not a part of this thesis' scope, and in addition, it is the aim of this chapter to study the building's shape on its own. For this reason, it is best to keep heating, cooling and lighting needs in separate fitness functions.

Case study 8 can then be described by the following set of equations:

$$Case\ Study\ 8 \begin{cases} Minimize & f_{1(x)} = Q_{H,nd}, \\ Minimize & f_{2(x)} = Q_{C,nd}, \\ Minimize & f_{3(x)} = Q_{E,nd}, \\ subject\ to & 14 \leq x_1 \leq 20. \\ & -45 \leq x_2 \leq 45. \end{cases} \tag{17.1}$$

17.1.5 Genetic algorithm inputs

NSGA-II explores 50 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 8		
Population Size (N)	50	
Number of Variables	2	
Number of binary digits	8	
Variable Domains	$x_1 \in [14, 20]$	$x_2 \in [-45, 45]$
Mutation Probability (p_m)	0.2	
End Condition	End after 50 generations	

17.1.6 Results

Case study 8 has a large amount of results, there are 4 different climates and 3 fitness functions. This means that there are 3 two-dimensional Pareto fronts for each climate. We will start by looking at a general overview of all of the results. Figures 17.4, 17.5, 17.6 and 17.7 show the objective spaces for Palermo, Torino, Frankfurt and Oslo respectively.

The most striking result from this study is the fact that orientation and room proportions in their own do not have a large influence in energy needs. The largest change in heating needs from a single climate comes from Oslo, and it barely reaches 2 kWh_t/m^2 a year. The largest variation in cooling energy need is seen in Palermo (3.5 kWh_t/m^2 a year), and for lighting it comes from Oslo (0.14 kWh_t/m^2 a year). These are very low variations, especially when we consider how different the orientations and building proportions are. These results support the findings of Mechri et al. (Mechri et al. 2010), building orientation and proportions are not very influential on their own. If we were to vary the openings in these buildings together with orientation and proportions, then we would expect to find much bigger relevances.

As is to be expected, heating needs are highest for Oslo and Frankfurt, while cooling needs are highest for Palermo. Lighting energy needs are quite similar for all climates, with a slight increase in need for Oslo.

Palermo

Heating needs for the office building studied in the Palermo climate are very small, they are negligible when compared to cooling needs. However, it is interesting to note that results for the Palermo study show very little contrast between heating and cooling needs. The best performing buildings for heating and cooling functions (A and B respectively) are quite similar, with only a slight variation in orientation angle. Both buildings A and B are 14×20 rectangles, and they are both almost perfectly oriented with the long facades due north-south. This orientation makes good sense for heating needs since it exposes the largest windows due south, and in so doing maximizes the solar gains for the winter. It is not so clear why this orientation is the best one for summer cooling needs (solution B). It can be argued that the solar paths for Palermo are high enough in the horizon, that the best way for the building to shield itself, is to depend on the shading overhangs created by the thick masonry walls.

Lighting needs for the Palermo climate are best met by solution C, it is a 14×20 rectangle that is oriented in such a way as to expose its long facades due east-west. This orientation exposes the most sunlight to the light sensors in the model.

Torino

Heating and cooling energy needs for the Torino climate are almost of the same magnitude. Meaning that the office building in Torino needs to be optimized for both of them equally. When compared to the Palermo results, in Torino we see a great deal of contrast in the heating and cooling needs. Interestingly, the Pareto front for heating and cooling needs is convex until one point when it becomes concave, showing quite different levels of contrast.

Solution A is the best performing one for heating in Torino. It is a 14×20 rectangle north-south exposed. This is congruent with the results obtained in Palermo, long south exposed windows increase winter solar gains.

Solution B is the best performing solution for cooling needs. This solution is quite different from the previous ones, it is a 16.7×16.7 square

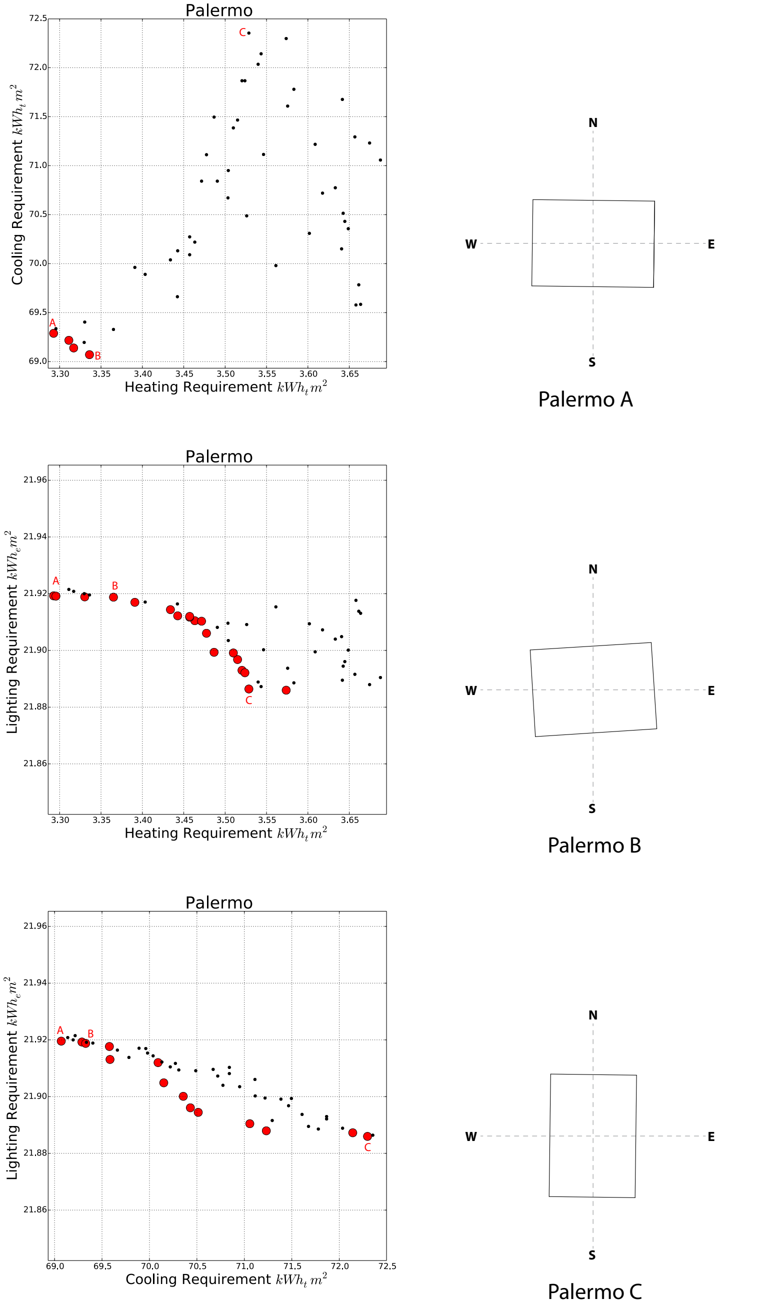


Figure 17.4: Objective spaces for Case Study 8 for Palermo.

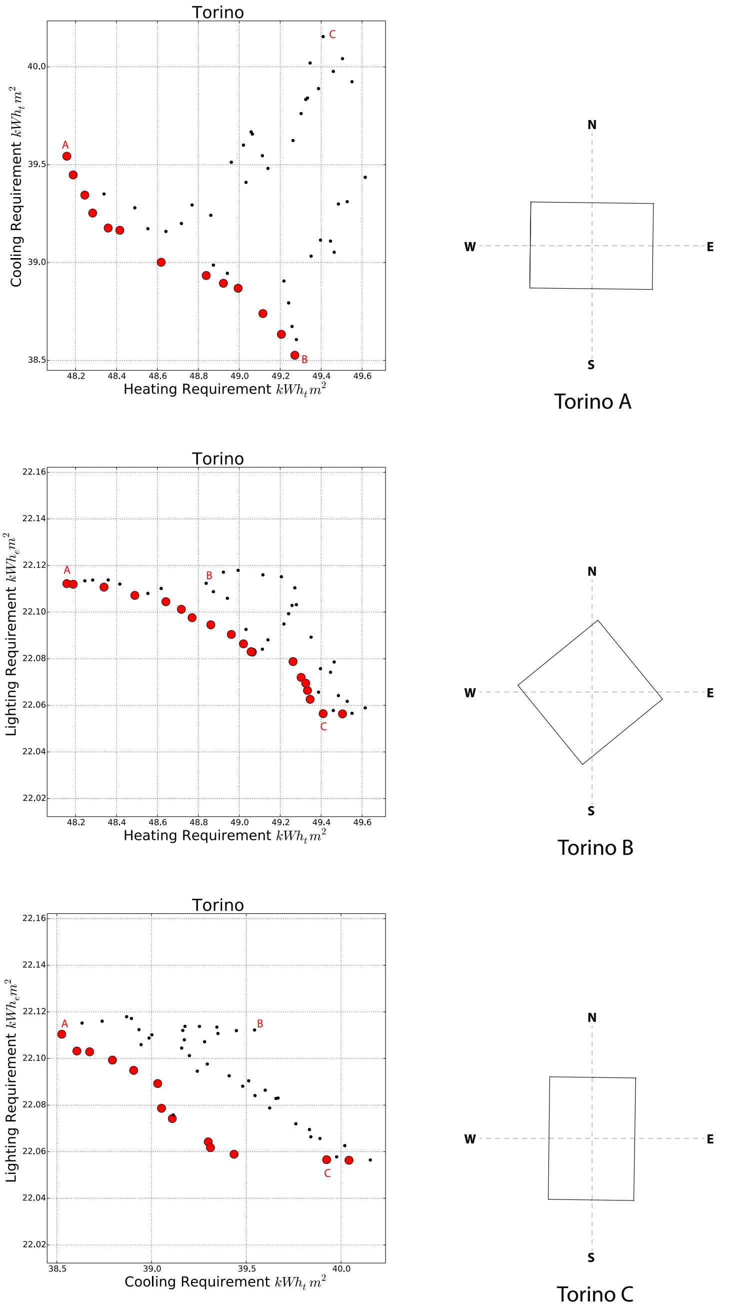


Figure 17.5: Objective spaces for Case Study 8 for Torino.

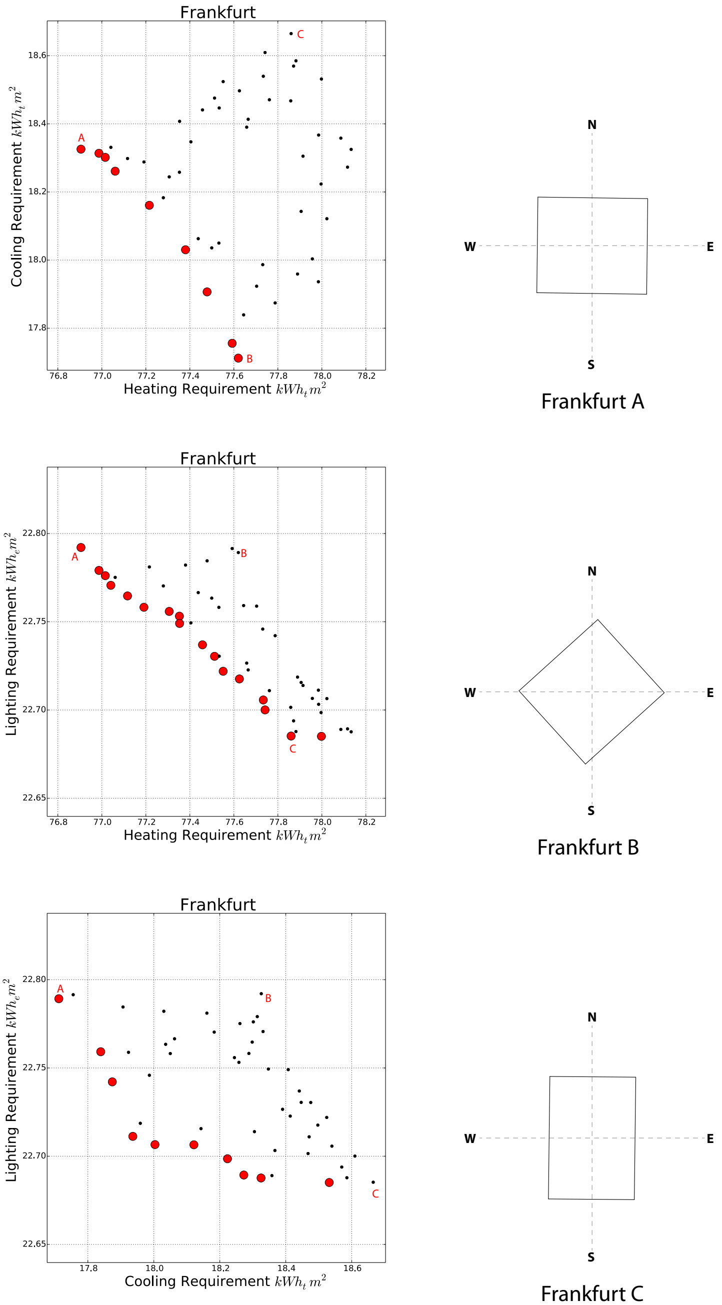


Figure 17.6: Objective spaces for Case Study 8 for Frankfurt.

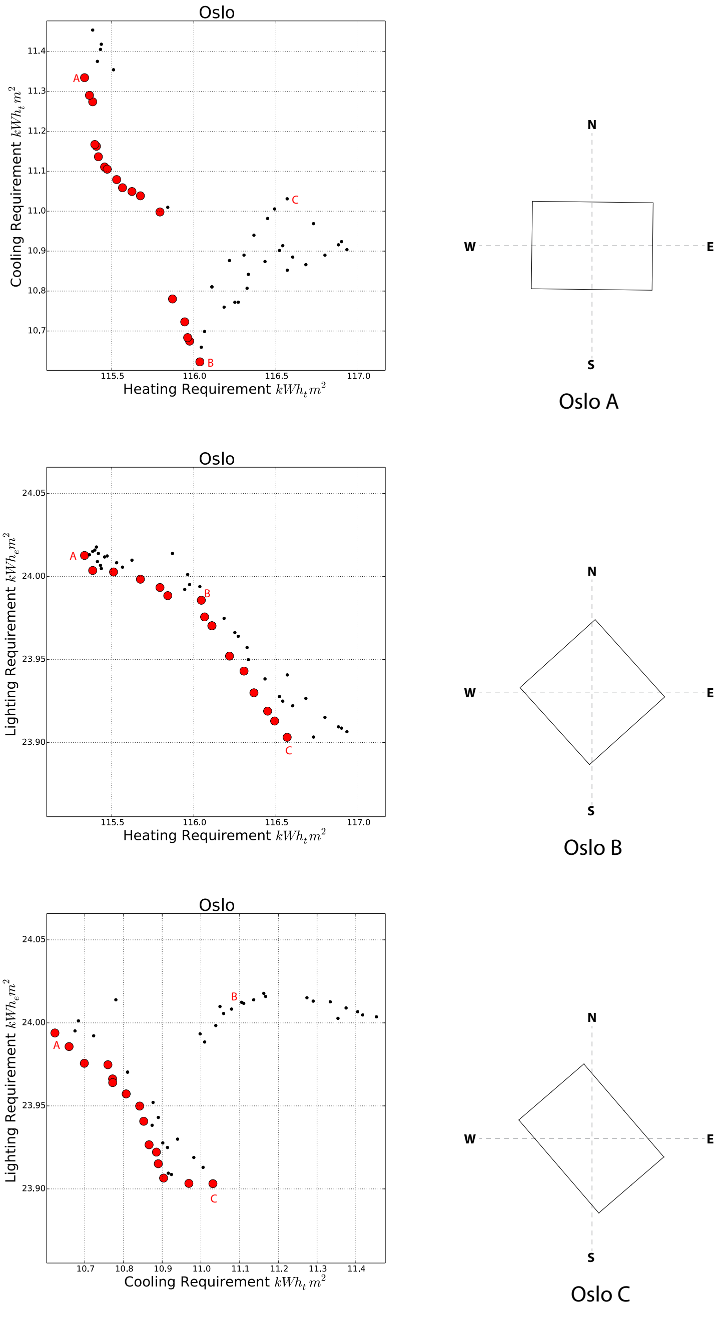


Figure 17.7: Objective spaces for Case Study 8 for Oslo.

that is oriented at an almost 45°angle from north. This solution is not very high performing in the Palermo study, but similar solutions will continue to appear in Frankfurt and Oslo. It is likely that sun paths for these cities in the summer are not high enough for the overhangs to shade during the summer. When this occurs, the only way the MOGA can find to shade internal spaces is to rotate the building, and place the opaque walls in the corners towards the east, west and south orientations. Another possible explanation for this 45°orientation is that the GA is trying at all costs to avoid having windows in the east and west orientations. The square form tends to make windows have better fin shading as well. These two possibilities are in contrast with one another, further investigation into this solution is required to fully understand the reason behind this orientation.

As was also the case for the Palermo study, the best performing solution for lighting needs (solution C) is a east-west exposed 14×20 rectangle. This solution is one of the worst performing solutions for heating, and the worst for cooling.

Frankfurt

In Frankfurt we see heating needs that are significantly larger that the cooling needs. Heating and cooling needs in this climate are also quite contrasted, the Pareto front having a concave shape.

Solution A is the best performing one for heating energy needs. It is a rectangle north-south exposed, but it is almost a square. This is to be expected as latitudes rise, sun paths become lower but they also reach farther into east and west that in lower latitudes. We can therefore assume that in oder to increase solar gains in Frankfurt, the MOGA is exploiting the east and west exposures, and not just southern one.

As was seen in the Torino climate, the best performing solution for cooling needs (solution B) is an oblique square. The best performing lighting solution is an east-west exposed rectangle (solution C).

Oslo

Oslo has the largest heating energy requirements out of all of the climates studied in this PhD thesis. Cooling requirements for Oslo are small but not negligible. Heating and cooling needs in this climate are also highly contrasted. Also in this case, the rectangular north-south exposed solution is the best one for heating (solution A) and the oblique square for cooling (solution B). Interestingly, for the Oslo latitude, the best performing solution for lighting is not north-south exposed. It is a 14×20 rectangle oriented at 45°from north. It appears that light is more efficiently introduced into the building when there is a long facade facing southwest. Looking at the sun radiation for Oslo, this makes sense.