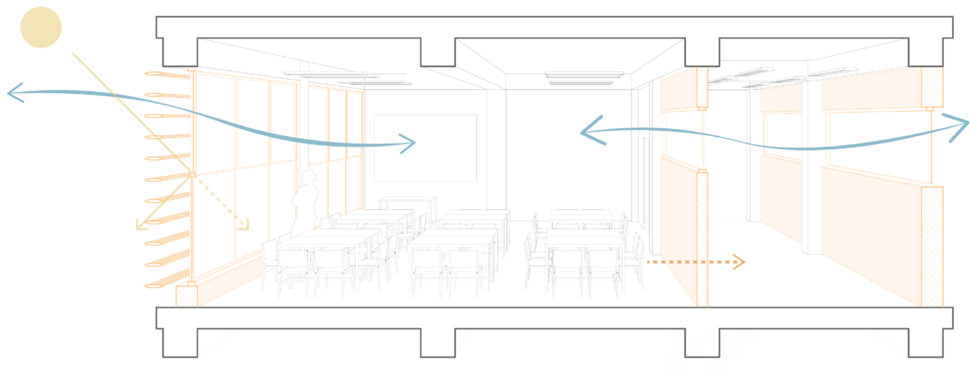
A computational method to guide sustainable energy upgrading of school buildings in Greece

through passive design interventions.



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... To Odysseas, for his continuous support these two years in TU Delft.

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Abstract

A big part of the schools in Greece fails to align with the regulations suggested by The School Building Organization in Greece, regarding their energy performance as well as the thermal and daylight comfort they offer. This study aims to inform the retrofit process of these schools, by proposing guidelines concerning the most impactful interventions in their passive design measures. For this, a Building Energy Simulation and Optimization method (BESO), was carried out. Such a method introduces multi-objective optimizations, which can help identify design solutions that need to satisfy multiple and possibly conflicting objectives. The optimizations were carried out separately for all three major climate zones of the country, using a typical classroom-corridor topology as a simulation model. The most impactful variables were extracted for each zone, along with a set of generated design solutions.

Contents

CHAPTER 1

Research Framework

1.1 BACKGROUND

According to the School Building Organization of Greece (OSK), in Greece there are more than 15.000 public school buildings, hosting more than 1.600.000 students of all educational stages, thus constituting a major part of the non-residential building stock. Out of these 15000 schools, approximately 41% is over 40 years old. Indicatively, 58.6% of the elementary schools were constructed prior to 1975, while there is also a significant 13% of schools, hosted in buildings originally designed for different purposes (Daskalaki & Sermpetzoglou, 2011).

In general, schools, due to their operational characteristics (operating only during weekdays, morning hours, from September to June), represent a rather small, yet significant, percentage of the building sector's overall energy consumption. SBO states that the total annual energy consumption for all these schools is around 270.000MWh. Other metrics obtained by the Center of Renewable Energy Sources, estimate an average annual energy consumption of school buildings in Greece of 92kWh/m², occasionally reaching 100 - 200kWh/m². This amount is considered relatively high, if we take Greece's moderate climate into account (Mavrogianni & Tsoukatou, 2006). Depending on the climate zone and building conditions, the mean heating energy of the school units corresponds from 72% to 85% - 88% of the total energy consumption recorded from different studies for school buildings of all grades around Greece (Daskalaki & Sermpetzoglou, 2011).

However, this amount of energy does not fully cover the schools' real needs, as in many cases classrooms do not offer an adequate comfort level. According to the School Building Organization of Greece (OSK), students feel cold during the winter, hot from spring through autumn and have to deal with poor light conditions throughout the school year (OSK,2008). Large amounts of potentially useful energy are being wasted because no energy saving measures are applied for the operation of schools (Daskalaki & Sermpetzoglou, 2011). Additionally, there are school buildings that lack any type of passive measures, primarily because no Buildings Insulation Regulation or Energy Performance Directive was in place in the legislation when they were constructed (Katsaprakakis & Zidianakis, 2017). Poor construction and the use of subpar products has in some cases affected the building's envelope, namely causing moisture penetration in the walls and roofs. (Katsaprakakis & Zidianakis, 2017). Literature also reports that even more recently constructed school buildings in Greece have various problems regarding Indoor Environmental Quality (IEQ), thus affecting the health and productivity of both pupils and teachers. In the same note, the excessive human internal gains caused by the high occupation density in classrooms (1.8 m²/pupil), increase ventilation requirements.

At the same time, lighting infrastructure is often outdated and lighting control is often absent. As an indicative example of natural lighting mishandling, according to surveys conducted as part of a study in 20 schools in Kozani, Northern Greece, artificial lighting was always on during working hours, even on a sunny winter day (Theodosiou & Ordoumpozanis, 2008). This was due to the fact that curtains or venetian blinds were kept shut to avoid glaring and over-lighting problems in the absence of natural lighting control.

Meanwhile, several computational methods that have been developed the last decades, offer many opportunities regarding retrofitting procedures and energy upgrades of existing buildings, but they are still unexplored when it comes to school buildings in Greece.

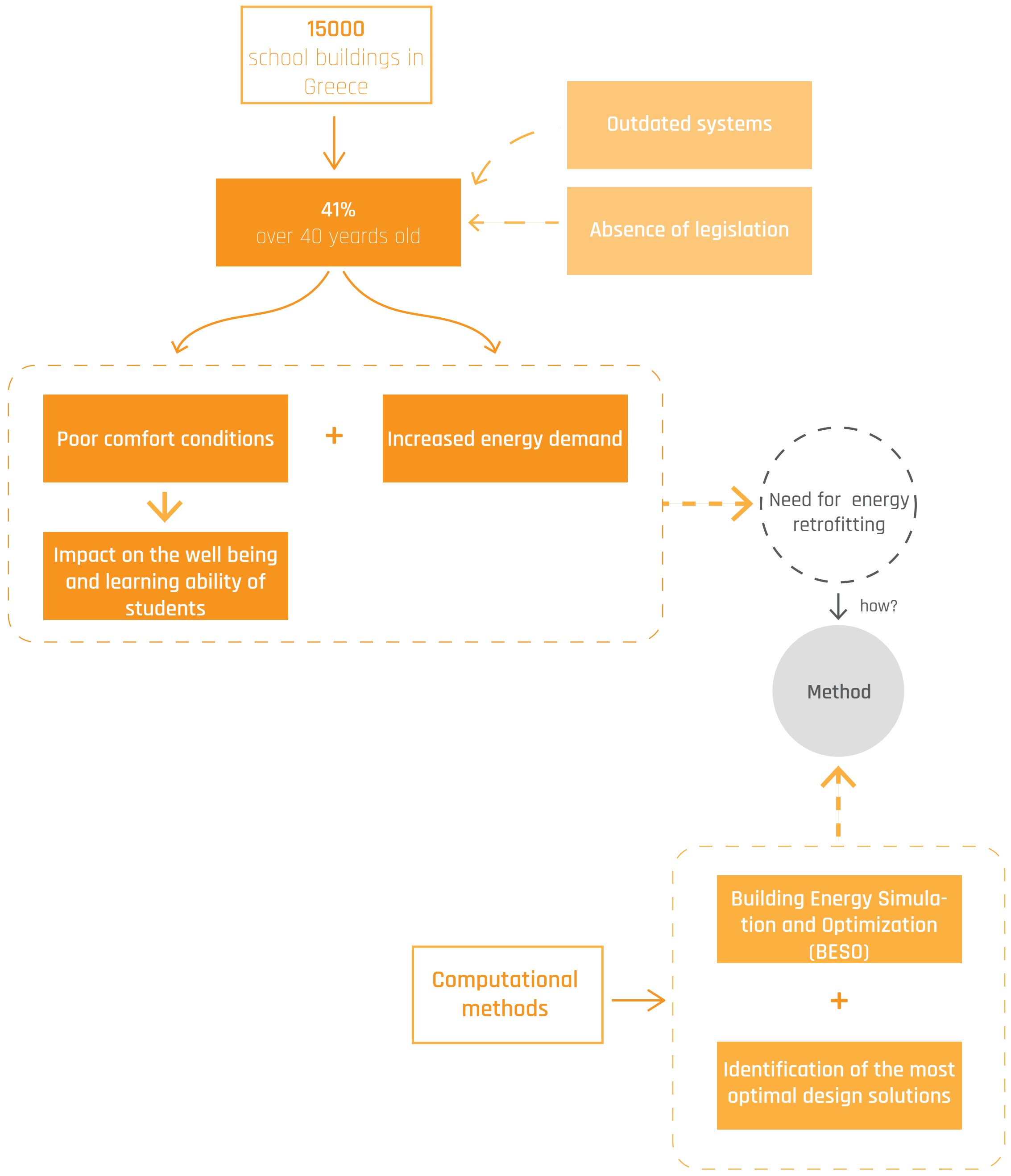


Figure 1.0: Flowchart of the problem statement

1.2 PROBLEM STATEMENT

Main problem

A high percentage of existing school buildings in Greece presents increased energy consumption and poor comfort conditions.

As described in the background, in Greece there is a large building stock of schools which fails to meet the current requirements regarding energy performance and sustainability standards. Despite the fact that OSK has been providing guidelines towards a sustainable design since 2007, there is a lack of detailed technical regulations to guide the retrofit process. This leads to refurbishments that only partly fulfil the needed requirements without taking into consideration all the various parameters that could contribute to the buildings' better performance and long term sustainability. This, not only results to environmental implications but also affects the educational activity since insufficient thermal, visual and noise comfort may negatively affect the learning process.

In addition to that, retrofitting procedures are complicated and include objectives that are often contradictory. Although numerous studies have been done regarding energy upgrade and improvements in existing school buildings in Greece most of them focus regionally, while only a few publications propose integrated solutions supported by thermal and energy analysis; the literature review illustrated that research in the area has mainly focused on the assessment of specific energy conservation measures and their contribution to the overall energy performance (Dascalaki & Sermpetzoglou, 2011), without addressing the problem holistically by taking into consideration possible passive measurements.

Despite the fact that existing school buildings in Greece present similar physical characteristics and can be thus easily categorized in a small number of categories, still, every building is unique and its upgrade is not considered a straightforward procedure. Designs must achieve high levels of performance for the lowest possible cost.

1.3 RESEARCH OBJECTIVE

Main objective

The objective of this research is the deeper understanding of the impact different passive measures (interventions) might have on the energy performance, daylight and thermal comfort of school buildings built between 60s and 80s in Greece, so as to guide their renovation towards current sustainability standards, ensuring comfortable and healthy school environments.

More specifically, this is done through the development of a computational method which combines simulation and optimization tools aiming to identify optimal designs for each renovation case. The method seeks not only to identify the most impactful passive interventions in terms of the schools' thermal and daylight comfort, but also those with the highest effect in lowering their energy demands.

Finally, objective of this thesis is to explore whether or not, and to what extent can such method add knowledge to this design problem and thus be used in real life, for such design problems, by architects.

Sub-objectives

Within the scope of the main objective several sub-objectives are defined:

- The understanding of the current conditions of school buildings, identifying the most problematic aspects in each climate zone.
- The investigation of possible passive measures and their integration in a computational parametric model.
- The exploration of the variables and the definition of their ranges. along with the definition of objectives for the optimization, based on the overall main objective.

1.4 RESEARCH QUESTION

Main research questions

The main research questions that this thesis seeks to answer is:

How can state-of-the-art Building Energy Simulation and Optimization (BESO) methods, guide the renovation process of existing school buildings in Greece, through passive design interventions, with regards to energy efficiency, daylight and thermal comfort?

And

To what extent can passive design interventions improve thermal comfort of the existing schools while minimizing their energy demand and retaining adequate daylight comfort?

Sub-questions

In addition, the following sub-questions will need to be answered:

- *What are the most determining passive design parameters to the energy demand and thermal comfort for each zone?*
- *What are the most optimal design solutions for each climate zone?*
- *How could such a method evolve to a tool that can be used in practise for the upgrading process of existing school buildings in Greece?*

In order to answer those questions, some background questions need to be answered first:

- What is the current state of school buildings in Greece when it comes to thermal and daylight comfort conditions?
- What are the main design parameters to be considered when it comes to passive design?

"How can state-of-the-art Building Energy Simulation and Optimization (BESO) methods, guide the renovation process of existing school buildings in Greece, through passive design interventions, with regards to energy efficiency, daylight and thermal comfort?"

1.5 APPROACH AND METHODOLOGY

Logical organization

The research is divided into 5 main phases as shown in Figure x. Firstly the introduction of the background and problem statement takes place, leading to the formation of the research questions. As a next step, literature review is conducted in order to create the foundation knowledge needed for the further development of the research by design phase.

The implemented method follows the Building Energy Simulation and Optimization (BESO) workflow. The method is applied to a specific case study, namely a generic classroom-corridor layout, whose energy, thermal and daylight performance is explored for the three main climate zones of Greece. It starts with the set up of the parametric simulation model in Grasshopper, using the Ladybug and Honeybee plug-ins. The simulation workflow is the applied to the geometry of the selected case study model, which has been modelled in Rhino. During this research by design phase, different parameters are explored based on their performance, which is assessed using EnergyPlus and Daysim for the energy and daylight analysis respectively. A preliminary analysis is then conducted to provide insight regarding the existing conditions of the case study model followed by the validation of the developed workflow in the DesignBuilder software.

The optimization model is then created using modeFRONTIER software, aiming to identify the best performing designs regarding the given objectives and by trying different variables. As a final step, the analysis and comparison of the optimization results takes place, where the most impactful variables along the best design solutions for each zone are being presented, followed by the discussion and conclusion of the research.

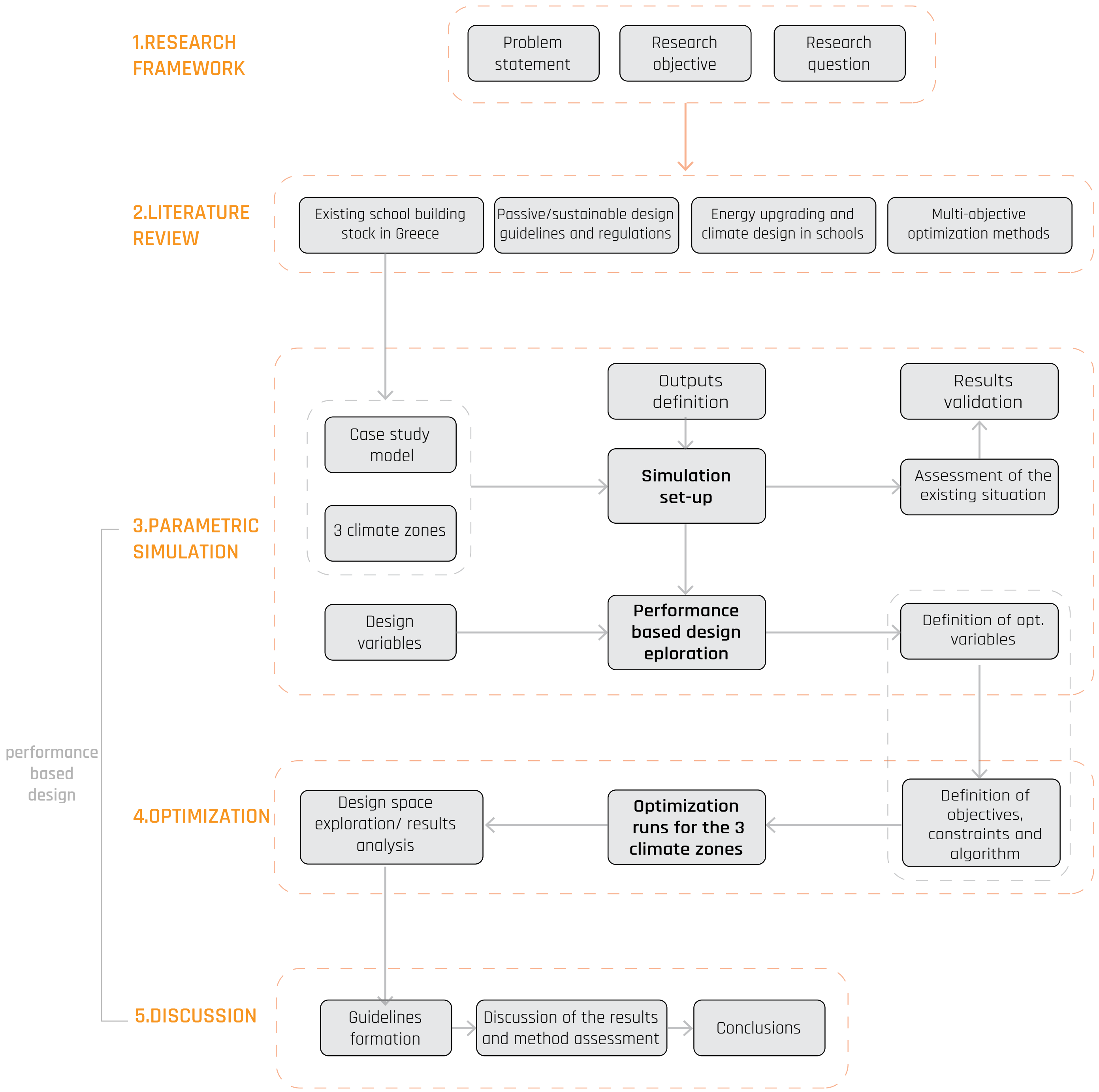


Figure 1.5: Methodology flowchart

1.6. RELEVANCE

Societal relevance

Students spend significant amount of hours in school buildings, which are often described as the "third teacher" as they have the ability to shape behaviours. It is thus crucial to ensure that school buildings provide students with healthy comfortable environments, improving the conditions for learning. Furthermore, by implementing sustainable strategies such as reducing dependency on fossil fuels for heating and lighting and responsibly sourcing and recycling materials, school environments can raise environmental awareness to future generations and guide sustainable lifestyles. As described by the ISO-15392 standard sustainability involves three primary aspects which are mutually interdependent and interrelated:

- the environmental aspect
- the economic aspect
- the social aspect

This research eventually tackles all three aspects in a direct or indirect way. The environmental aspect is tackled through one of the main research objectives which is to minimize the energy demand in school buildings and thus the reduction of dependency on fossil fuels for heating and lighting. The economic aspect lies on the energy and time efficiency that may be achieved by developing such a renovation process while the social aspect lies in the fact that comfort conditions in classrooms ultimately ensure better learning abilities for the students.

Scientific relevance

The process of converting an existing school building into a modern sustainable, energy efficient building is a demanding task. The trade-offs are mainly revolved around four categories. Energy efficiency, comfort, feasibility and educational impact. This research, focusing on the upgrade of school buildings in Greece as a case study, aims to make the correlations of the two first categories clearer, in terms of the parameters that define them, and provide more knowledge regarding the possible passive design measurements that can be applied during such renovation processes. Understanding the possibilities, risks and challenges of the proposed method will ultimately provide valuable insight regarding the future development of such renovation processes.

CHAPTER 2

Literature Review

2.0 Introduction

This chapter provides an overview of the literature studies conducted within the scope of this thesis, which can be categorized in three main categories. First, literature research was made to investigate the situation of the existing school buildings in Greece regarding building physics conditions and energy performance aspects. The outcome of this research determined the problem statement.

The second part includes on overview of the guidelines for bioclimatic design provided by the School Building Organization of Greece (OSK), along with regulations regarding comfort conditions in schools. In addition to that, studies that have been done regarding retrofitting and upgrading of existing school buildings will be shortly presented in order to provide more information on what are the main parameters affecting a school building's performance are as well as the most common practices for upgrading such buildings. Moreover, a brief description of the available assessment methods regarding daylight comfort will be given.

Finally, an overview of the optimization methods applied in building scale will be given, comparing different processes, emphasizing the challenges and focusing on the ones that are more related to the retrofitting processes.

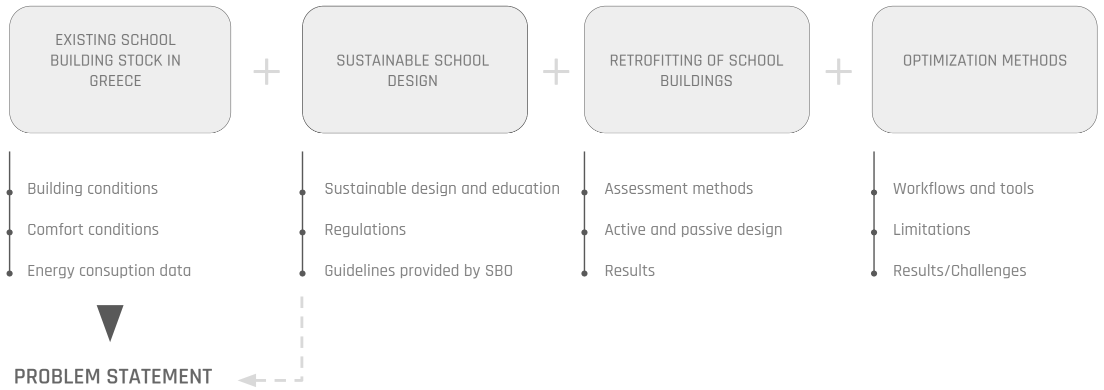


Figure 2.1: Research categories

2.1 Existing school building stock in Greece

2.1.1 School building typologies

School buildings in Greece can be categorized in 4 main categories based on their construction year. (Figure 2.2). First category includes schools built before 1960, which are usually made out of stone walls and wooden roofs with no insulation but often high thermal mass. The second category includes schools constructed between 1960 and 1981, when the SBO was founded and lots of school buildings were constructed around the country in a standardized way, based mainly on economical criteria. This standardization neglected the different climatic conditions and needs of each location. Until the 1970's, when more typologies were introduced, the ones used were either a typical linear corridor-classrooms layout or an L layout. The construction was mainly carried out with concrete structure and brick walls, without insulation and with single glazing metal framed windows. After 1981 when insulation regulations were introduced, school buildings were covered with insulation (Styrofoam or polyethylene) but only partly, since the structural elements are most commonly left uncovered. In 2007, SBO launched the *Guidelines for Bioclimatic school design* (later described in this report) and school buildings built from then on comply with them, thus ensuring better indoor, thermal and daylight comfort with the minimum energy consumption.

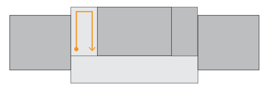
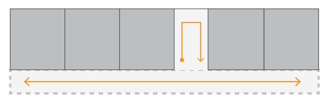
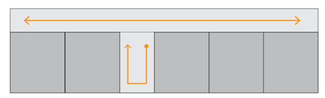
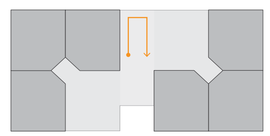
School type	Construction period	Schematic plan
Old stone building	Before 1960	
Open corridor linear layout	1960-1980	
Closed corridor linear layout	After 1960	
"Athena" type	After 1980	

Figure 2.2: School building typologies in Greece (until 1990). Adapted from: C.R.E.S., 1995

2.1.2 Classroom characteristics

According to the regulations, a typical classroom of a junior high school or high school fulfils the following requirements (OSK, 2008):

- Capacity: Max 30 students
- Minimum interior dimensions: 6,9 m
- Free height: ≥ 3,0 m
- Required window surface: 1/5 of the classroom's facade

Classrooms typically consist of approximately 10-14 desks organized in 3 or 4 rows plus the teacher's desk located on one side along with the board.

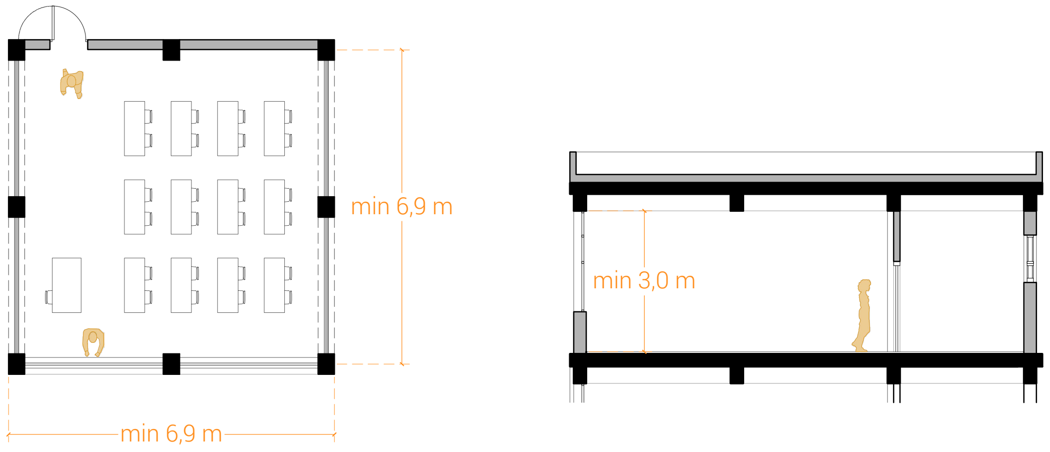


Figure 2.3: Typical classroom plan layout and section.

2.1.3 Current comfort and energy conditions

Students spend 1/3 of their day in their school environment which plays an important role in both their physical and mental health. Nevertheless, as introduced in the problem statement, various literature studies, indicated in Table 2.1, state that a large percentage of the school building stock in Greece does not provide adequate comfort conditions while consuming increased energy amounts.

In this paragraph, some additional information, to what was already discussed in the background and problem statement, is presented to offer a deeper understanding of the current energy, thermal and visual conditions of the school buildings in Greece.

AUTHOR	YEAR	TITLE	OBJECTIVE	RESULTS
Theodosiou et al.	2008	*Energy, comfort and indoor air quality in nursery and elementary school buildings in the cold climatic zone of Greece*	Investigation of the energy efficiency, thermal environment and indoor air quality in school buildings in climatic zone C of Greece.	Almost all of the examined buildings are inefficient and fail to provide the recommended thermal and air-quality environment. Possible measures include low-cost ones like the installation of light shelves for better solar and daylight control, the improvement of window air-tightness, and better lighting control.
Dascalaki et al.	2011	*Energy performance and indoor environmental quality in Hellenic schools*	IEQ and energy performance assessment in 135 school buildings in Greece.	Two-thirds of the school buildings fail to meet the standard requirements regarding their thermal envelope construction. Absence of proper control leads to excessive energy consuption.
Vagi F. & Dimoudi A.	2011	*Analysing the energy performance of secondary schools in N. Greece*	Determine the most urgent needs and energy upgrade proposals. Maximise energy performance and sustainability.	Natural lighting, reduction of infiltration losses, controlled ventilation during the winter, shading and natural ventilation are the most important aspects.
Santamouris et al.	1993	*Energy consumption and the potential for energy conservation in school buildings in Hellas*	Assessment of 238 school buildings. Action proposals for energy upgrade.	Energy consumption for heating can be reduced 43.9% by adding insulation to the buildings, 6.1% by using double glass windows.
Gaglia A. G. et al.	2007	*Empirical assessment of the Hellenic non-residential building stock, energy consumption, emissions and potential energy savings*	Collection of data to determine the potential energy conservation in the Hellenic non residential building stock.	Data regarding the current consumption of the non-residential building stock. There is potential for energy savings through energy efficiency measures applied to the non-residential building stock. More spesifically, for school buildings in Greece, thermal energy demand can be reduced by 6–205 GWh and the electrical energy demand by 15–143 GWh.
Klifopoulou M. & Tsaousi X.	2014	*Investigation of the energy performance of school buildings in Thessaloniki, Greece*	Energy simulation of 4 school buildings in Thessaloniki, to gain deeper understanding regarding the problematic aspects.	Poor current performance of the school buildings. List of actions are proposed for each building to guide its energy upgrade.

Table 2.1: Previous studies regarding the conditions of the existing school building stock in Greece.

Energy performance

Improper passive design and insufficient installation systems result in increased energy consumption in school buildings, which as already mentioned, do not satisfy the required comfort conditions anyway. Absence of insulation and inadequate window properties lead to large heat losses through the shell. Inappropriate design, poor maintenance and over-sizing of heating systems are additional factors that lead to increased heating demand and worse comfort conditions during winter months. The majority of greek school buildings is equipped with a central heating system of hydronic radiators using heating oil. Heating oil burners, are often old and inefficient (at the range of 75% efficiency) while the heating systems are often oversized, not well maintained and in most cases lacking operation control provision

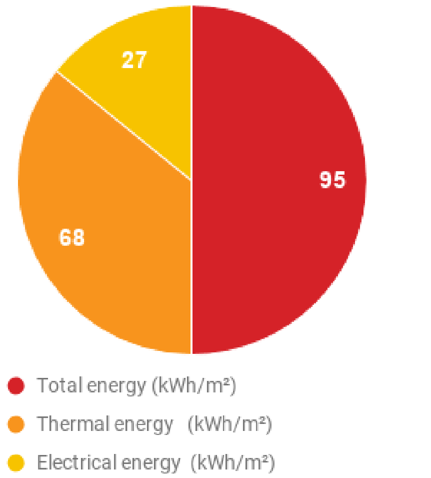


Figure 2.4: Average annual energy distribution for school buildings in Greece. Adapted from: (Klifopoulou M. & Tsaousi C., 2014)

The non-residential buildings sector in Greece consumes 47.6% of the electrical energy and 8.2% of the thermal energy required by the whole building sector in Greece, based on measurements that were done in 2001 (Gaglia et al., 2006). Energy efficiency measures can thus result in multiple positive impacts when applied in the non-residential building stock. Mores specifically, for the school buildings in Greece, Energy Conservation Measures (ECM) can reduce the thermal energy demand by 6-205 GWh and the electrical energy demand by 15-143 GWh (Gaglia et al., 2006).

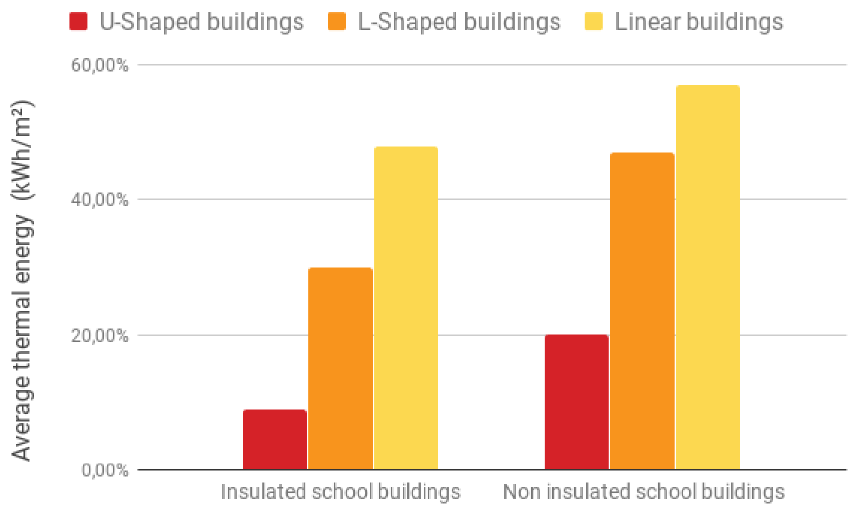


Figure 2.5: Average thermal energy (kWh/m2) for different school building typologies. Adapted from: (Klifopoulou M., 2014) p.25

Interestingly enough, research data obtained by CER and OSK show that among different typologies, the simple linear configuration of school buildings, has the highest energy consumption (Figure x) (Klifopoulou M. & Tsaousi C., 2014). This makes the importance of focusing in this typology even greater.

Thermal comfort

Regarding thermal comfort, during winter months students feel cold while classrooms in zones A and B are overheated from spring to autumn. Uncontrolled natural ventilation and air penetration through the connections between openings and walls results in large thermal losses and the creations of air currents.

A previous study (Dascalaki & Sermpetzoglou, 2011) on a typical school building showed that even during the mild spring period of monitoring, on average, 60% of the recorded indoor temperature, one-third of relative humidity and about 17%-35% of concentrations, were inconsistent with indoor conditions prescribed by international standards. The most frequent IEQ complaints reported during the subjective evaluation are related to insufficient ventilation, noise disturbance, glare and thermal discomfort.

Visual Comfort

Regarding visual comfort, the most common problem that students face is glaring, while it has also been observed that light is not equally distributed in the classroom, creating dark areas. This is due to the bad orientation, wrong design of the openings, absence of proper shading and improper artificial light installations.

Artificial lighting is often provided with inefficient incandescent light bulbs or fluorescent lamps for the interior spaces and energy intensive floodlights for the exterior yards, while lighting control is most often absent. As an indicative example of natural lighting mishandling, according to surveys conducted as part of a study in 20 schools in Kozani, Northern Greece, artificial lighting was always on during working hours, even on a sunny winter day (Theodosiou & Ordoumpozanis, 2008). This was due to the fact that curtains or venetian blinds were kept shut to avoid glaring and over-lighting problems in the absence of natural lighting control.

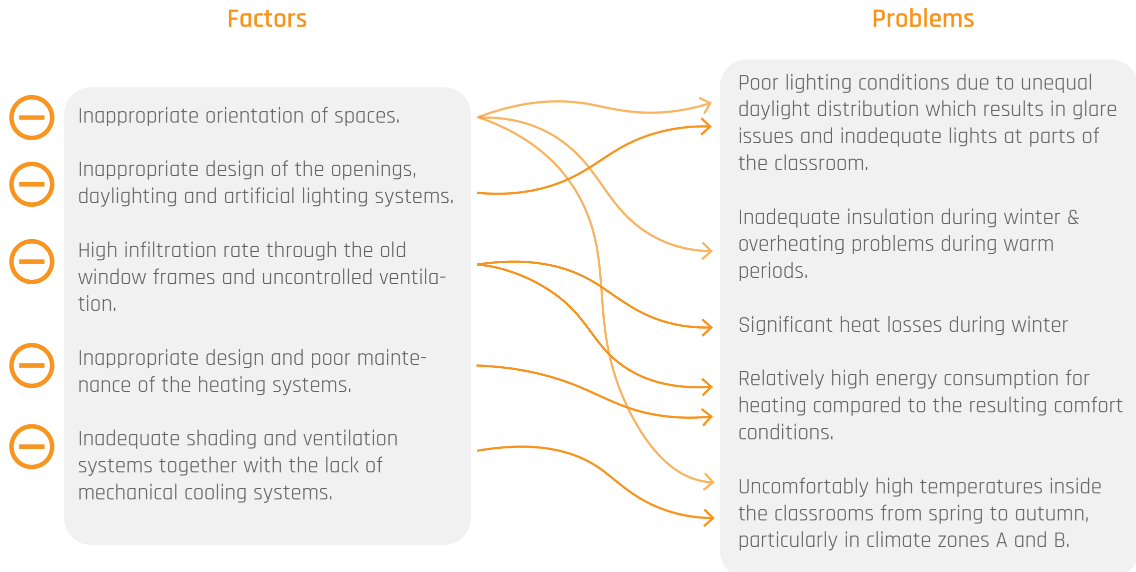


Figure 2.6: Summary of the main problems of the existing school building stock in Greece, along with their factors. (Adapted from: C.R.E.S, 1995)

2.2 Guidelines of Sustainable School Design provided by School Building Organization of Greece (OSK)

2.2.1 Introduction

When it comes to school design in Greece, the regulations are given by the School Building Organization (OSK). As it was already mentioned, since 2007, OSK provides guidelines regarding sustainable school design. As it is described in the guide, the main goal of energy design for classrooms, is the realizations of a modern , energy efficient and environmental friendly spaces, that will ultimately meet all the required safety specifications and ensure better operating condition and fertile ground for the educational activities. Within the scope of this thesis the focus is exclusively on the exploration of passive design measures and systems. Such a priority makes sense within the general philosophy of first trying to improve buildings passively as much as possible before proceeding to the application of active systems.

Passive design refers to a number of design integrated strategies applied to buildings in such a way so as to facilitate the best exploitation of solar energy for heating the buildings and of winds to ventilate them and cool them down.

In practice, regarding architectural elements, passive sustainable school design comes down to the following basic elements, as they are provided by OSK (OSK,2008):

- Proper placement/orientation
- Daylight design strategies
  - Openings
  - Shadings
- Natural ventilation
- Insulation
- Eco-materials

In this chapter, a summary of the above mentioned categories will be given. OSK guidelines is the main source of information, nevertheless, additional sources have been added to provide more knowledge regarding topics that are lacking information within the guide. The ultimate purpose of this chapter is to collect information about all the possible parameters that are related to a school building's passive design so as to be used later on the design phase.

Figure 2.7: Categories of passive design strategies described within OSK guide for Bioclimatic School Design.

2.2.2 Proper placement/orientation

The placement of a school building should be such so as to allow for:

- Adequate daylight during day time when school building is functioning.
- Maximum solar gains inside the rooms during winter.
- Sun protection during summer.
- Cross ventilation based on the prevailing winds.
- Reduction of noise coming from the external environment.

In general, the most preferable orientation for classrooms according to OSK is considered the south, as long as it is protected from the direct sunlight, and the north, which offers steady indirect daylight all day. East and west openings should be avoided as it becomes harder to control daylight in such orientations. The exploitation of sunlight has to be such so as to increase daylight and thermal comfort while minimizing the energy consumption of the building. Therefore, before the construction of a school building starts, analysis need to be made to determine the needed solar gains based on the function of the space, the orientation and the climate zone. Regarding solar gains what is important to know is the solar irradiation altitude and angle of incidence for specific location. In that way, the amount of daylight entering the building or the needed shading area can be determined, making sure there is enough direct sunlight during winter but not during summer (OSK,2008).

2.2.3 Natural lighting design

When it comes to daylight comfort within school classrooms, there are three main criteria to be taken into consideration:

- The amount of illuminance reaching the work plane.
- The distribution of daylight within the space.
- The protection from glaring due to increased direct sunlight.

Minimizing direct sunlight entering the room while maximizing the usage of the diffused natural daylight is primary goal when it comes to daylight design for schools. (orientation and shading). In order to ensure equally distributed daylight within the classrooms, opening should be placed in both sides rather than in only one which is the most common situation in current schools. Openings can have a regular form or the form of skylights. When classrooms are placed on both sides of the corridor, it is suggested that the corridor roof is either higher or lower than the classrooms ceilings so as to allow daylight entrance (OSK,2008).

Walls and ceilings should preferably be painted in white or light colours as they then have the ability to reflect part of sunlight and distribute it to the space. Light Shelves on the openings are highly recommended so as to reflect and bring light to the deeper sides of the classrooms while their efficiency is also enhanced by applying light coloured and reflective materials (OSK,2008).

Regarding the protection from the glare, OSK once again suggests the creation of proper shading devices on the openings as well as reflective materials that will diffuse the sunlight to the interior space contributing to less shading/lighting contrast that are often the cause for glaring issues.

Room	Target illuminance values (lux)
Classroom	300
Offices	300
Laboratories	300
Library	500
Multi-use room	300
Corridors	150
Sanitary areas	150
Boiler rooms	150
Storage rooms	150
Canteen	300
Laboratories/design studios	500

Table 2.2: Target illuminance values for school spaces according to OSK (OSK,2008).

Electric light should be enabled only when natural daylight is not sufficient according to the standards. It should also be designed such so as to allow lights to be turned on only in a part of the classroom where natural light might be insufficient a time.

Openings

The location, the orientations and size of the openings are of primary importance when it comes to lighting design. In general there are two main ways to allow natural light enter interior space:

- Through the roof (with roof openings/skylights)
- Through facade openings

A simple rule to estimate the size of an opening during the early design face is calculating that the daylight will reach approx 1,5-2 times the height of the window lintel. It is thus preferable to have openings placed on high heights. View to the outside should also be taken into consideration depending on the function of the space.

Shadings

Shadings are very much needed especially in the Mediterranean climate of Greece where overheating problems occur quite often. Shading elements should ensure the reduction of solar heat gains during summer while protecting from glaring all year long.

During summer months, exterior shading is preferred so as to block solar radiation before it enters the building. On the other hand, during winter months, interior shadings are recommended so as to allow solar heat gains enter the room but at the same time prevent from glare. Knowing the indicative indoor temperature of a room and the mean outdoor temperature one can determine the period for which shading is needed. In addition to that, based on solar irradiation altitude, the angle of incidence and the opening size, the needed shading geometry can be determined.

Shadings can be integrated parts of a buildings structure such as cantilevers, dynamic exterior or interior shading devices or a combination of the above. Dynamic/movable exterior shadings are preferable due to their adaptability and ability to block heat gains before entering the interior space during summer, but due to their increased cost, OSK suggests the creation of permanent

exterior shadings in combination with movable interior ones. The most impactful parameter when it comes to shading design is the orientation. The most suitable shading type for south openings is the horizontal exterior shadings. Parameters to be taken into consideration when calculating the depth of the shading are the distance of the horizontal shading form the top of the window, the window height and shading inclination if any. Regarding east and west openings, due to the continuous sun movement, the optimal shading solution is the dynamic vertical shading, tough its maintenance and stability might be critical issues.

Summarizing the main shading categories, there are:

1. Horizontal exterior permanent shadings
Its most suitable for south orientations. It can have the form of cantilever or reflective light shelves or louvres. The portions should be such so as to create angle between the shading and the bottom of the window of 55 degrees angle for 40 latitude and 60 for 36 latitude.

2. Vertical exterior permanent shadings
Recommended for east or west openings. Might also be inclined towards to horizontal plane. The length of the extensions is determined by the rule of 55 degrees angle for all the latitudes of Greece.

3. Exterior dynamic shadings
This is usually done through metal horizontal or vertical louvres that can move/rotate manually or automatically.

4. Interior dynamic shadings
It is recommended for south, east and west orientation. Venetian blinds attached to guides are suggested as the best option.

5. Planting as shading
Deciduous trees might be an excellent way to shade openings especially in east and west orientation. Besides the shading function, planting also contributes to the thermal performance of a building and creates a pleasant microclimate around it.

Concluding, among the different types of shadings, the exterior permanent ones seem to be the most feasible solution in terms of cost and maintenance. Exterior shadings are also preferred due to the fact that they block solar heat before entering the space and therefore will be selected for this particular study.

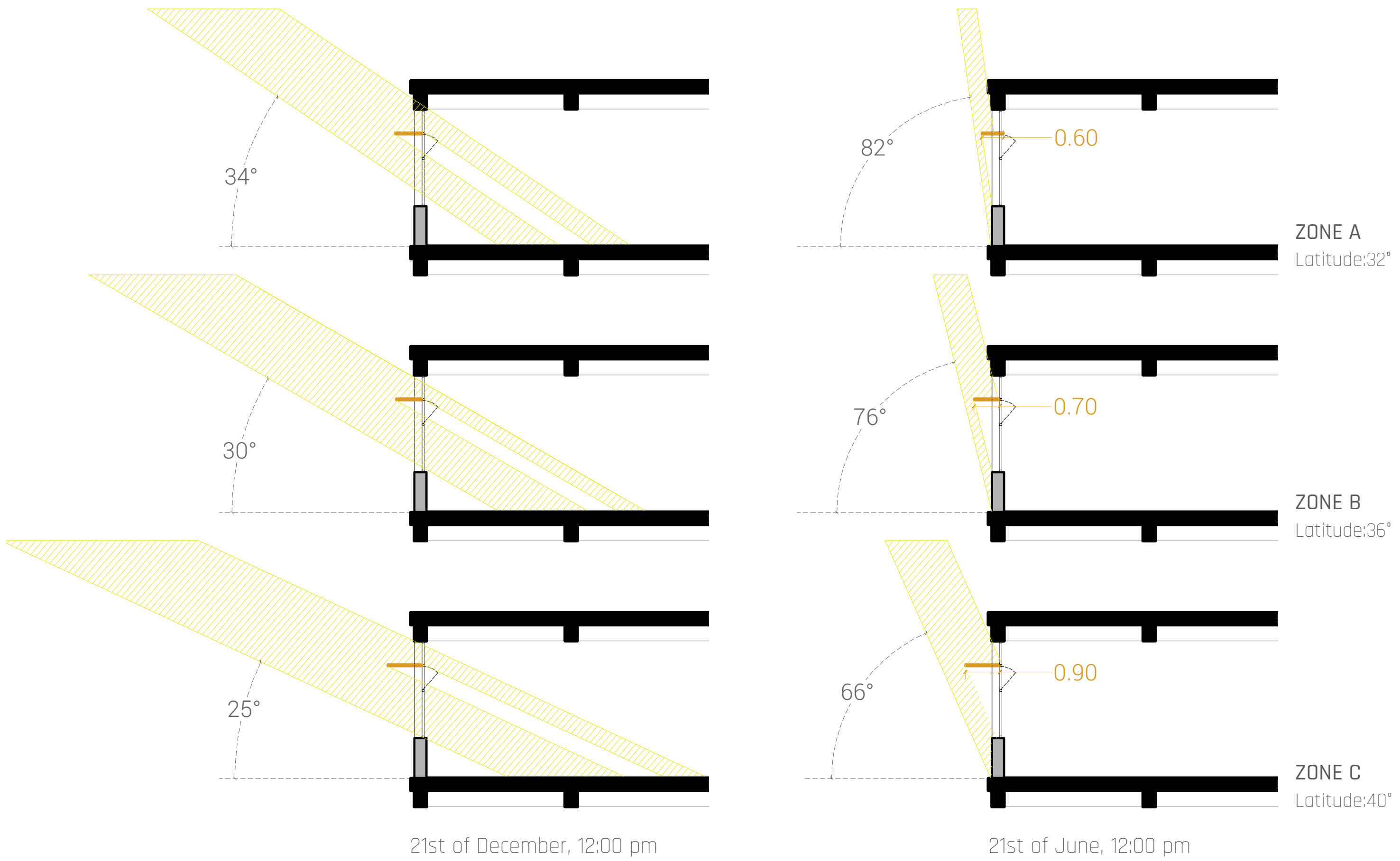


Figure 2.8: Indicative shading depth calculation for each climate zone in Greece, based on the latitude and the sun's angle of incidence for given time of the day.

2.2.4 Natural ventilation

Public school buildings in Greece do not provide mechanical ventilation or cooling systems. Natural ventilation is mainly done through wind driven natural ventilation which is also used to cool the building down. Wind force driven ventilation is generated by pressure variations caused by the wind. Airflow moves inwards and outwards through openings placed on facade sides. When designing a school building and in order to succeed optimal natural ventilation conditions, the following aspects have to be considered according to OSK (OSK,2008):

- Placement of the building volume along the dominant wind direction.
- Placement of the inlet openings towards the windward side and of the outlet openings towards the leeward side.
- Use of planting, windscreens and other wall/geometric elements that can be arranged in such a way around the openings so as to create various wind pressures enhancing natural ventilation.

- The locations of the openings determine the wind speed inside a room. It is thus suggested to have inlet outlet openings in opposites sides (cross ventilation) rather than in only one (single sided ventilation).
- Location of inlet openings is of primary importance. If they are placed too high it might happen that there is no air circulation at the human height level.
- Size of inlet and outlet openings should be roughly the same. If there is a need for a higher wind speed inside the space, outlet openings can be increased by 25% in relation to the inlets.
- Having cross openings placed at the same height should be avoided. This is probable due to draught creation.
- Night conditions should be taken into consideration, nocturnal ventilation can be very efficient for cooling down a building.
- Inlet geometry can direct wind speed
- Surrounding topography and architecture must also be taken into account since it might contribute to the direction of the dominant winds.

The second type of natural ventilation is the thermal force driven ventilation based on the stack-effect due to temperature differences. In that case air moves from high density areas to low density areas, When air temperature in a room is higher than the outside air, a vertical air flow is naturally caused if there is a higher and a lower opening in the room. This phenomenon is more applicable during winter when there is a higher temperature difference between interior and exterior air. The most important factors that have to be taken into consideration when it comes to thermal driven ventilation are the following (OSK,2008):

- The area of the inlet opening should be the same as the outlet opening.
- Width to height ratio of the openings has to be bigger than one, meaning that openings should be placed horizontally.
- The minimum vertical distance between inlet and outlet opening should be 1,5m, but the bigger this difference is the better airflow is achieved.
- Shafts and staircase can be used to enhance the stack effect at a building scale.

2.2.5 Insulation

As it was mentioned in the background, all the school buildings that were built before 80's suffer from poor thermal and energy performance due to the absence of insulation. Adding wall and roof insulation is therefore a mandatory step during the renovation process in order to meet the current indoor comfort demands. Insulation can be either added to the exterior side, can be integrated in the wall (in case of rebuilding the wall) or can be added from the inside (OSK,2008).

Adding exterior insulation is the most secure way to avoid thermal bridges as all the structural elements can be fully covered along with the brick walls. Attention should be given to the materials that are used on the exterior side as they have to be water resistant. Adding an extra layer of a thermal insulating plaster can also contribute to the reduction of thermal losses of the existing building. Studies have shown that adding exterior insulation to existing buildings can save up to 42% of energy for climate zone A, 24% for climate zone B and 17% for zone C, per year

(OSK,2008).

Interior insulation is preferred when there is the need for protection of the interior space towards too high outdoor temperatures. In that case, according to OSK, interior insulation proves to be more efficient as heat concentration of the exterior envelope is prevented as heat is released to the exterior environment during night and cooler hours. Adding interior insulation can save up to 57% in zone A, 38% in zone B and 27% in zone C (OSK,2008). Whereas interior insulation seems to be more effective, it is in general not suggested by OSK as it might lead to condensation of the interior side of the walls. Exterior insulation is much more preferable as it helps retaining more stable indoor temperatures.

Adding insulation in between the brick walls is a common practice as well. In that case attention should be given to the protection of the structural elements (columns/ beams) so as to prevent thermal bridges (OSK, 2008).

Besides the direct way of applying insulation there are possible indirect ways that can also contribute to the improvement of a building's thermal performance. This, in case of renovation, can include the addition of external skin (such as perforated wood) on a distance from the existing walls which can create a microclimate between the existing facade and the extra layer. By keeping a distance of 5cm between the two layers, air can pass through, acting as an insulation layer while at the same time the existing walls are protected from big amount of direct solar irradiation. Another way to have indirect insulation is by adding semi-open or buffer zone spaces that will reduce the heat exchanges from interior to exterior (OSK,2008).

Requirements regarding maximum thermal transmittance align with the national Regulations for Building Energy Efficiency/ Part 8: Minimum requirements as they are presented in Table 2.

Bulding element	zone A	zone B	zone C
Exterior roofs	0,5	0,4	0,38
Exterior walls	0,6	0,5	0,44
Floors of semi-open spaces	0,5	0,4	0,4
Floors adjacent to ground or unconditioned spaces	1,5	1	0,38
Walls adjacent to unconditioned spaces	1,5	1	0,7
Windows	3,2	3	2,8
Glass facades	1,8	1,8	1,8

Table 2.3: Maximum U-values per element for each climate zone (W/m² K). Source: http://www.opengov.gr/minenv/?p=184

Sustainable insulating materials

In general, a material is considered sustainable when it fulfils the following criteria:

- Low embodied energy
- Minimum waste during production
- No toxic pollutants
- Recyclability

Material name	Thickness (m)	Conductivity (W/(mK))	Density (kg/m3)	Spesific heat J/(kg K)	R-value (K·m²/W)
Thermal insulating plaster	0.003	0.07	-	-	0.042
WOOD FIBRE (WF)	0.05	0.04	100	-	1.25
EXPANDED CORK (ICB)	0.05	0.04	125	1500	1.25
MINERAL WOOL	0.05	0.037	60	840	1.35
CELLULOSE	0.05	0.038	25.6	-	1.32
WOOD WOOL (WW)	0.025	0.09	460	1470	0.27

Table 2.4: Properties of recommended eco-materials for insulation. Source: (WE QUALIFY, n.d.).

Common insulation materials such as rockwool, glasswool, polyethene and polystyrene are considered to be dangerous according to IARC. Environmentally friendly insulation materials that can be found in Greece are:

- Linen/flax insulation
- Iso cotton insulation
- Expanded cork
- Cellulose

2.2.6 Window properties

Regrading window properties the only suggestion from OSK is the use of low-e double glazing and of wooden frames with thermal breaks, while as indicated in Table x, the maximum thermal transmittance value (U) for windows is 3.2 W/m² K for zone A and 2.8 W/m² K for zone C. Looking into different double glazing types in the market we find the following types, based on the solar heat gain coefficient (SHGC) and the visible transmittance (VT).

SHGC is expressed as a number between 0 and 1 and indicates the amount of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward (EFFICIENT WINDOWS COLLABORATIVE, nd). The lower a window's solar heat gain coefficient is, the less solar heat it transmits, and therefore, the most preferable it is for hot climates. On the other hand, low SHGC values might keep away solar heat when needed, during winter months. Finding the best trade off between overheating problems and solar heat utilization depends, besides the climate context of the building, on the orientation and shading type.

VT indicates the amount of light, within the visible spectrum range, that penetrates a glazing material (Commercial Windows,n.d.). Values vary from 0.1 (for highly reflective coatings on tinted glass) to 0.9 for uncoated clear glass). Higher VT values allow in general more daylight in the interior spaces, ultimately limiting the need for electric lighting.

By combining different SHGC and VT values, various window types can be achieved fitting different climate needs (Table x). Since no suggestions are given by OSK regarding specific values for these two properties, their further exploration is considered a valuable step.

	Window types			
	Material frame	U-value (W/m² K)	SHGC	VT
Double-Glazed, High-solar-gain Low-E Glass	Metal frames with thermal breaks or non metal frames	0.41-0.55	0.41-0.60	0.51-0.60
Double-Glazed, Medium-solar-gain Low-E Glass	Metal frames with thermal breaks or non metal frames	0.41-0.55	0.26-0.40	0.51-0.60
Double-Glazed, Low-solar-gain Low-E Glass	Metal frames with thermal breaks or non metal frames	0.41-0.55	≤0.25	0.51-0.60

Table 2.5: Different window types and their properties. Source: https://www.efficientwindows.org/gtypes_2lowe.php

2.2.7 Application of sustainable design guidelines in existing school buildings

The existing building stock of schools is really significant and their renovation is of primary importance. The challenge thus becomes how to apply the sustainable design guidelines in those buildings. For that, OSK does not provide specific info rather than two pages of general recommendations (See appendix A). The recommendations are categorized based on the 3 different typologies of the existing school buildings, being the school buildings built before 50s, the ones built between 60s and 80s and the ones built after 80s. Within the scope of this thesis, only the recommendations regarding the 2nd category, where the selected case study belongs, will be further described in an attempt to bring more light to the renovation possibilities.

The first suggestion is regarding the transformation of open corridors to closed ones to either block or gain heat gains. Secondly, the addition of insulation on the exterior walls is suggested, especially to the buildings that have thin (single brick) walls. Buildings with thicker walls have less heat losses due to the increased thermal mass. Nevertheless, adding insulation to their exterior side is suggested as well, though the cost of such an intervention might be too expensive. Primary gate of heat losses in buildings with high thermal mass is the roof, and thus insulating the roof in such cases is strongly recommended as well. Replacing window frames which are currently metal and badly mounted allowing high infiltration rates, helps in the reductions of heating load as well as it shown in the same Figure. Addition of solar systems, such as transforming south corridors to sun space along their whole length or partially, by broadening some parts can lead to up to 28% heat load reduction for zone C and 8,4% for zone B. Adding thermosiphonic panels on the south walls so as to preheat air before entering the classroom is suggested as an intervention though no specific data are provided for the effectiveness of such a system. Cooling through natural ventilation may have a large impact in the heating load for all three zones as it is presented in Table 2.9.

	Estimated Heat load reduction		
Proposed measures for buildings built before 1980	zone A	zone B	zone C
Making the open corridor close, to either block or take advantage of the heating load.	-	-	-
Roof insulation	14%	4,5%	14%
Window replacement	6%	4%	7%
Addition of passive solar systems	-	8,4%	28%
Placement of solar heat panels for preheating air before entering classrooms	-	-	-
Cooling through ventilation	-	63-81%	55-79%
Shading placement	12-37%	20%	-

Figure 2.6: Estimated Heat load reduction for different interventions for climate zones A,B and C. Source: (OSK,2018)

2.2.8 Conclusions

As an outcome of the literature research, passive design parameters potentially affecting a school building's daylight and thermal performance were collected, categorized and organized based on their applicability in both a renovation and parametric/computational context. Figure 2.10 maps these parameters diagrammatically indicating their correlation.

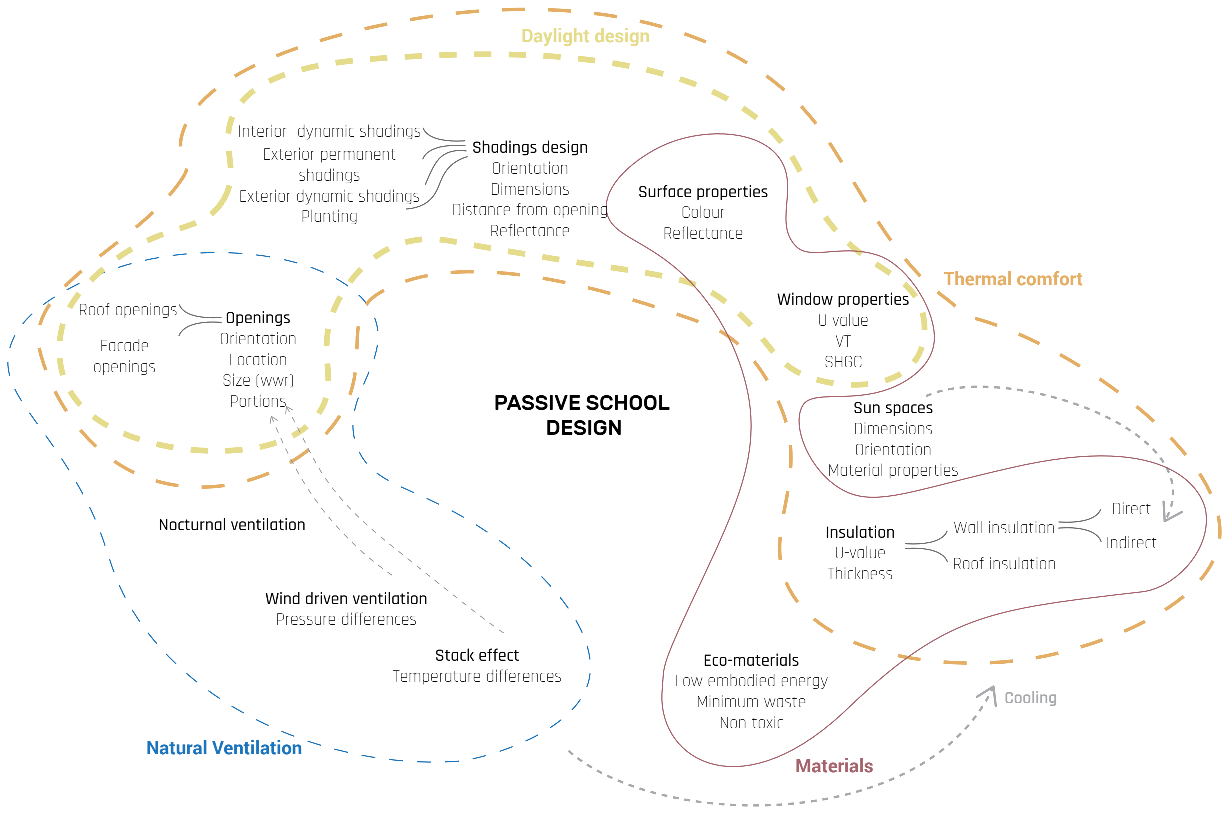


Figure 2.10: Mind map of the passive design parameters relevant to daylight and thermal performance

A renovation process, as opposed to a new building construction, introduces some extra limitations regarding the possible interventions, since certain design parameters are static or embeded to the existing structure. For instance, the location and orientation of the building, its structural grid and its dimensions are factors that have to be taken as given. Other factors such as occupancy rates, the schedule of the building etc., are also considered static as they are directly linked to the building's functions, while parameters such as ventilation rates must adhere to some comfort standards as they are defined by the existing regulations.

Despite the fact that OSK provides recommendations regarding possible interventions in the existing school buildings, these are still quite limited and general, highlighting the need for further exploration of the topic.

2.3 Climate context

In general Greece's climate is characterized as temperate Mediterranean. From a climatological standpoint, the calendar year can be divided in two main seasons, the cold, wet winter season running from mid March through mid October and the warm, dry season lasting for the rest of the year. Sunlight is high almost all year. However, a wide variety of climate types is seen in various areas of the country. This is caused by its topographical configuration, namely the big altitude differences and the constant interchange from land to sea. Such climate variations, can be observed even in places very close to each other. The location of a school building significantly affects its energy performance and needs. The aforementioned climate variations result in significant differences between the energy consumption and thermal demands of schools located in different areas (OSK,2008).

More specifically, according to the current Thermal Insulation Regulation, the country is divided in 4 climate zones as shown in Figure x. Considering the limited area of zone D, this thesis is focusing in climate zones A, B and C.

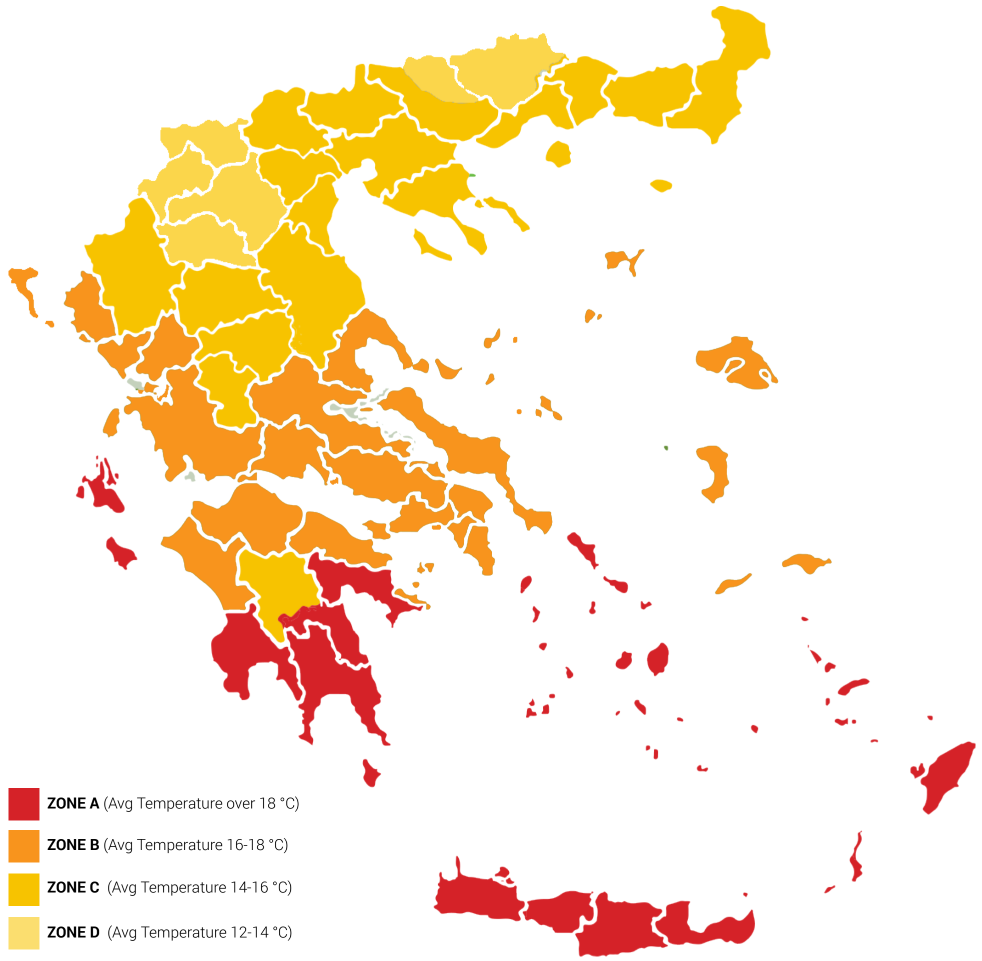


Figure 2.11: Climate zones in Greece. Adapted from: (Papamanolis N.,2015)

School buildings located in zone A, a zone characterized by mild climate, have bigger demands on cooling rather than heating. These demands are fairly balanced for school buildings in zone B. Lastly, in zone C, the cooling demands are very low while the heating demands are very high.

For the analysis, weather files from Herakleion, Athens and Thessaloniki were used as representative cities of the three climate zones.

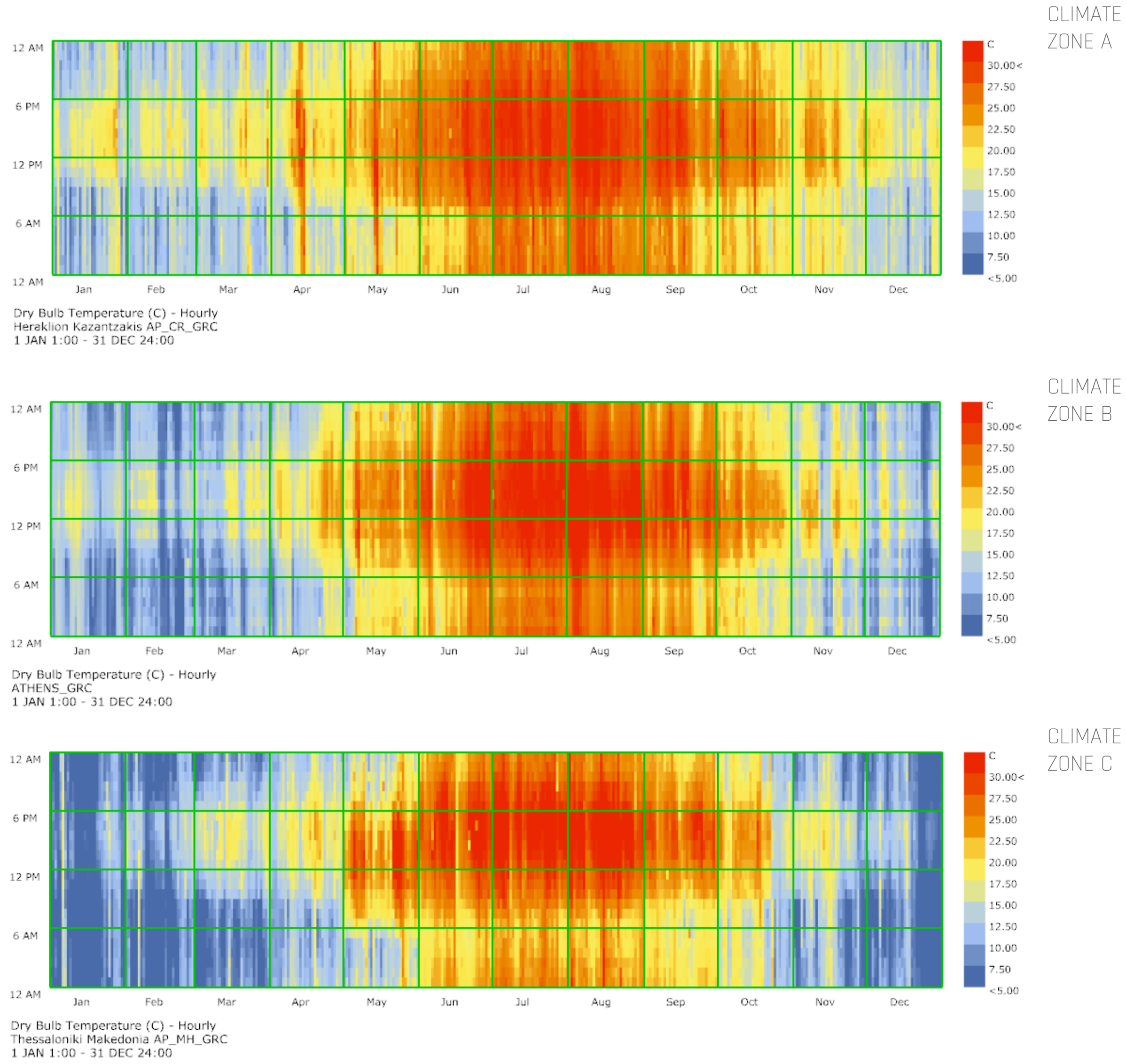


Figure 2.12: Temperature graphs for the three main climate zones of Greece, as exported from Ladybug, Grasshoper.

2.4 Daylight and thermal comfort metrics

2.4.1 Daylight

What is daylight?
Daylighting is the process which uses daylight to address and control the lighting effects in buildings, such as ensuring adequate light inside a room, highlighting or hiding certain objects while also reducing the energy costs of succeeding the desirable indoor conditions.
Achieving a well-lit space goes a lot further from simply exposing a building or space to natural sunlight. Even the definition of well-lit is subject to space perception based on cultural backgrounds, but also varies a lot depending on the specific function the building serves. Moreover, oversupply of daylight, also introduces risks of glare as well as overheating the space, thus increasing its cooling demand.

Why is daylight important when it comes to school design?
The importance of daylight conditions within the context of educational buildings is made apparent by the strong interest shown in understanding and improving them. First attempts towards addressing and controlling the daylight conditions date back to 19th century UK. Introduction of new teaching methods after the second world war, suggested classrooms with higher energy demands in covering air conditioning and lighting needs, consequently downgrading the importance of natural daylight (Baker et al. 2002). This view was justifying its feasibility and reduced window design, not only in the fact that these growing energy needs would be counteracted by decreased cooling demands, but was also backed by educational studies, that at the time were suggesting that windows to the outside distracts students, thus reducing their performance. However, in the 1980's architects already looked more back to more traditional, climate-based designs which benefited greatly from daylight (Constanzo,2017). Since the 1990's the European Union conducted several studies on daylight integration within buildings, which in turn showed promising results towards improving visual comfort, reducing energy demands and ultimately creating a more inspiring environment (Fontoynont,1999). Other studies also highlighted the risks of introducing glare and thermal discomfort in certain orientations and shading choices, especially with today's extensive use of projectors and interactive boards in classrooms.

2.4.2 Daylight metrics

Illuminance
There basic metric for daylight is illuminance. Illuminance in a spatial point, is defined as the ratio of the luminous flux, on surface around the point, to that surface area (Constanzo, 2017). Measuring illuminance in a point is straightforward and only involves the use of a luxmeter. However its value is dynamic with respect to time, so subsequent metrics must be obtained at different times in order to comprehend its temporal behaviour. According to most standards, the minimum desired average illuminance in a classroom is 300 lux.

Uniformity Ratio
Starting from this basic metric of illuminance, several other metrics have been introduced. Uniformity Ratio(UR), measures the ratio of the minimum to the mean illuminance over a given surface, effectively defining the uniformity of illuminance in a space. Standards suggest at least 0.6 UR in the working plane, or at least 0.4 UR in the surroundings for artificially lit classrooms.

When dealing with site-lit classrooms where only daylight effects is taken into accounts the lower bound of 0.3 UR is deemed more realistic (Constanzo 2017).

Daylight Factor
Daylight factor(DF) is defined as the ratio of indoor to outdoor illuminance for an overcast sky and is typically expressed as a percentage(%). A DF of 3% typically corresponds to indoor illuminance of 300 lux since the average outdoor overcast-sky is around 10.000 lux (Costanzo, 2017). The DF by definition does not consider non-overcast sky conditions.

More recently other metrics have been introduced, trying to overcome the drawbacks of the aforementioned metrics, mainly the fact that they ignore daylight's temporal behavior and changes. These metrics, referred to as climate-based metrics, derive from calculations over a time-span, while also introducing actual climate conditions. Such metrics are:

Useful Daylight Illuminance
Useful Daylight Illuminance (UDI) is defined as the percentage of occupancy time when a predefined range of daylight illuminances at a point in a space is met. A typical range of 300 - 3000 lux illuminances is often perceived as desirable (Mardaljevic et al, 2009). An accepted UDI is typically defined as 50% for the mentioned range.

Daylight Autonomy
Daylight Autonomy (DA) is defined as the percentage of hours of occupancy when only a minimum illuminance threshold, typically 300 lux, is succeeded only by natural light (Reinhart, 2001). Its value is obtained by hourly calculation of the illuminance in a model taking not only climatic data into account, but also the geographical position as well as annual weather data. The percentage of DA measured can on one hand describe the performance of daylighting, but also on the other hand the electric energy consumption required to maintain this minimum (deluminaelab, nd).

Spatial Daylight Autonomy (SDA)
SDA is defined as the percentage of floor area exceeding a predefined illuminance level for a certain amount of annual hours. Thus, sDA is a zonal metric, i.e., meaning that it derives one value for each room (Reinhart, 2001).

Annual Sunlight Exposure (ASE)
ASE indicates the percentage of the occupied area where direct sunlight illuminance is over a defined value, typically 1000 lux, for a defined amount of hours per year, typically 250 (Illuminating Engineering society, 2012).

To assess glare issues, we use luminance-based metrics. Luminance measured in a given direction is a physical quantity indicating the luminous intensity emitted in that direction per unit visible source area (Carlucci, 2015). Luminance is measured in nit (1 nit = 1 cd/m2). There is no globally established value for the maximum luminance in order to prevent daylight glare (Wienold, 2006).

Discomfort Glare Probability (DGP)
DGP aims to establish a measurement on the probability a person is disturbed by glare (Wienold, 2006). It is calculated as a function of the vertical eye illuminance introduced by the light source

(Ev), the source's luminance, and the angle of the source seen by an observer. Since DGP takes the user's response to glare into account, it is considered the most appropriate metric for glare (Constanzo, 2017).

Spatial Visual Discomfort (SVD)
SVD is defined as the percentage of occupied space where DGP is measured over 0.45, for at least 20% of the occupancy time; One proposed indicative value for a comfortable classroom was set to < 10% when excluding all points less than 0.5m away from the windows (Zomorodian, 2017).

However, based on a study on the performance of several glare metrics conducted by Raquel Viula 2019, it was concluded that none of the available glare metrics seem robust enough to predict the effect of glare across space. For this, in this thesis, it was chosen not to simulate and address glaring issues all together.

The simulation tools used for this thesis offer only some of the mentioned daylight metrics. More specifically, the Honeybee plugin used for the simulation, calculates DA, SDA and UDI. Finally from this subset, DA with a minimum threshold of 300 lux was used. The reasons and implementation of the daylight simulation is further discussed in Chapter 3.

2.4.3 Thermal comfort assessment

The assessment of the thermal comfort of an interior space can be a very complicated task, as numerus factors can determine it, ranging from human related ones (such as the clothing, activity or even psychology of the occupants) to physical ones related to air and radiant temperature, humidity level, air circulation etc (Parsons K., 2014). Several metrics have been developed to help quantify thermal comfort in buildings, taking into account almost all of these factors.

Among those, the most commonly used, and the ones that have also been integrated into simulation software (such as Honeybee and Ladybug, which are later used in this study) are the PMV (Predicted Mean Vote) based on Fanger's research in the 70's (van der Linden,2013) and the Adaptive Thermal Comfort model.

PMV is used for buildings with a centrally controlled indoor temperature, while the Adaptive Thermal Comfort is used for naturally ventilated buildings where windows can be opened (van der Linden,2013), and is thus more suitable for the evaluation of school buildings in Greece where no mechanical ventilation is applied.

Within the scope of this research though, and among all the factors that affect thermal comfort, only the interior air temperature will be taken into account ,as the most determining one and in order to simplify the assessment process. Thermal comfort is thus perceived as the percentage of hours during which interior air temperature falls within the acceptable range of values as it will be further described in Chapter 3.

2.5 Energy upgrades of school buildings

2.5.1 Introduction

In this chapter, a short overview of previous studies, regarding school building retrofitting and energy upgrades, is being presented, in order to provide information regarding the different applied methods and interventions.

In their study, G. Dall'O' and others (Dall'O' et al., 2013), proposed improvements in 14 schools in Italy, taking into consideration both technical and economical aspects, aiming to ensure the requirements for LEED certification. The methodology starts with the definition of measures that lead to a reduction in the consumption of resources; The objectives are then defined as following: maximizing energy performance and sustainability. The measures that use renewable energy are preferred. When defining the measurements, all natural solutions that can help control the climate and lighting within the building, such as green roofs, green facades, natural shading systems, passive solar and lighting by daylight systems, are considered. Finally the evaluation of sustainability targets takes place, in accordance with the LEED® rating system. Regarding the economical impact, the cost of building envelope retrofit had the highest cost item with 53.2% of total cost, heating systems retrofit was second with 29.7% of total cost.

Similarly, Katsaprakakis and Zidianakis (2017) proposed both passive and active measures to upgrade 10 schools in all the different climate zones of Greece (Crete, Thrace, Thessaly, Macedonia). Passive measures to decrease heating and cooling loads include application of external insulation in the inadequately insulated building envelopes (walls and roofs), installation of new windows and doors with double glazing and metallic insulated frame, in cases of existing openings with single glazing. In addition to that, the construction of shading overhangs above south orientation openings was proposed, in cases there was no shading protection along witha a Green roof and various other active systems. The main objectives were obviously the energy upgrading of schools, the reduction of the operating cost, and the introduction of a strong and highly effective demonstration tool for the promotion of the energy conservation concept on the young and easily cultivated school ages. The fact that the schools were located in different climate zones in Greece significantly affected the energy consumption and the optimum combination of the proposed energy upgrading interventions due to the different conditions and solar irradiation.
In their study, F. Vagi and A. Dimoudi (2011), determined the most important factors to improve indoor quality of secondary schools located in climate zone c in Greece. They divided the proposed measures based on their impact per season (heating and cooling period).

While the above studies provide a useful insight of the different parameters that affect a schools buildings performance and what the impact of each one of these may be, the are not strongly related to the design aspects. The impact of different architectural strategies on a schools energy performance have been examined by Zomorodian and Nasrollahi (2013) where different combinations of passive measurements were tried. The study suggests that optimum infiltration rate, optimum window to-wall ratio and optimum ground adjacency level of the building surfaces have the highest effect on decreasing the primary energy demand of the studied school building. On the contrary, the optimum roof form, compactness of the school building form and the optimum class arrangements are considered as the architectural strategies that have the minimum impact on reducing the primary energy demand in the studied school building. The results show that only by assigning optimum architectural strategies the lighting energy demand was reduced

42%, the heating energy demand 11% and the cooling energy demand 47% in comparison to the existing school building with thermal insulation and the defined infiltration rate. The optimum amounts of all parameters are assigned in one model and the primary energy demand has been compared to the base case model. Results show that the primary energy demand has decreased 31% only by optimum architectural strategies, without any change in the building materials and construction parameters. This reduction is increased to 40% by considering construction parameters (insulating the thermal envelope due to the recommended regulations and decreasing the infiltration rate). Also the average indoor temperature was decreased by 3°C during warm months and increased by 2°C during cold months when mechanical heating and cooling systems were turned off. As the author suggests, the architectural strategies defined in this study could be used in other school buildings in hot and dry climates. This method of architectural energy efficiency could also be applied in schools in the other climates and therefore is relevant to the current research project.

Passive measures	Active systems
Thermal envelope improvements Window to wall ratio Insulations (walls and roofs) Window replacement Implementation of shading Green roofs Nocturnal ventilation Surface colours	PVs Biomass heaters, Hybrid Cooling Lighting equipment Ground source heat pump (GSHP) Heat Recovery Systems Control Systems Efficiency of boilers Thermostats, Ventilation fans

Table 2.7: List of passive and active measures that were most commonly implemented in previous studies regarding retrofitting process of school buildings

2.6 BESO

2.6.1 Introduction

Architectural design is a complicated process including various objectives that need to be fulfilled. These may be quantitative (e.g. achieving a certain level of energy consumption or thermal conditions) while others are hard to be evaluated by computational means (e.g. Aesthetics, architectural integration etc). Different computational methods have been developed the last decades, that integrate optimization processes, aiming to offer optimal solutions, with respect to all the different objectives. Their general framework can be described as performative computational architecture (Ekici et al., 2019) and includes three main stages, starting from the form finding, moving to the performance evaluation and finally the optimization process.

Optimization is the process of iteratively minimizing or maximizing a certain quantity by adjusting the values of input parameters, while respecting some limit values also referred to as constraints. More specifically, the input parameters, either discrete or continuous, are fed to a set of solvers, a black box, which evaluates the behavior of the under analysis model and eventually generates its response.

In this study, the Building Energy Simulation and Optimization(BESO) method was further researched and finally implemented. BESO is an emerging, promising and innovative technique, aiming to tackle the problem of conserving energy and developing energy efficient design methods, still however not widely adopted as a design practice. It basically conducts energy simulation and optimization until the optimal solution is found based on predefined design criteria.

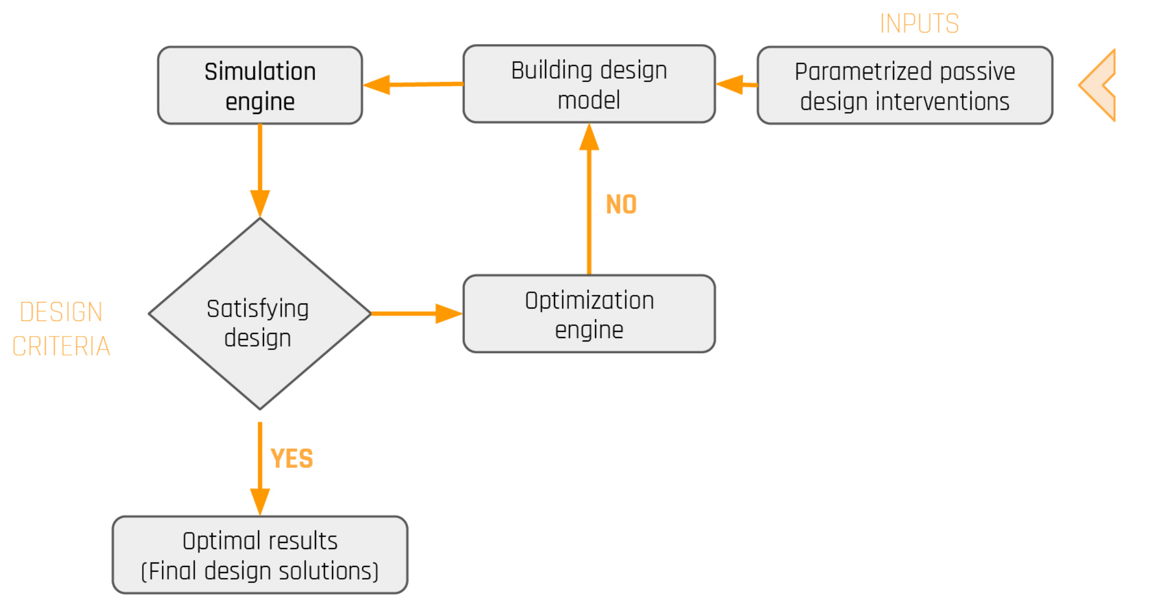


Table 213: Beso workflow. Adapted from: (Z.Tian et. al., 2017)

2.6.2 Optimization in BESO

All BESO implementations share a similar setup and workflow when it comes to the process followed during the optimization step.

Optimization software

There are several software tools that can carry out a BESO optimization. Some of them come in the form of plug-ins directly integrated with design simulation tools, e.g Octopus for Grasshopper (food4rhino, nd) or Optimo for Dynamo (dynamobim, nd). Other, external to the simulation process software, can also integrate with them and consequently run the optimization process. Such tools are modeFRONTIER, Matlab and GenOpt among others. For this study modeFRONTIER was used. ModeFRONTIER is a multi-objective optimization platform, which seamlessly integrates with simulation software like, in this study's case, Grasshopper through integration nodes and offers a user-friendly interface which also facilitates data visualization and decision making (esteco, nd).

2.6.3. Optimization workflow in BESO

Three phase BESO is divided in the pre-processing, the optimization and the post processing phase. In the first, a baseline energy model is constructed. During the optimization phase, the optimization properties themselves are defined, such as the objective functions and constraints, the input variables as well as the algorithm that will carry out the optimization. Lastly, in the last post processing phase, the visualization and interpretation of the results obtained is done. Sensitivity analysis BESO methods, also introduce an intermediate step for exploring the design space, in order to speed up the algorithm (Z.Tian et. al., 2018).

Definition of inputs and objectives

In each optimization problem the definition of inputs (variables) and objectives takes place first. In this paragraph, variables and objectives that were used in previous studies are being shortly presented. Carlucci et alumni (Carlucci et al., 2015), used the U-values of external walls, roof and windows along with strategies to control shading devices to optimize four objectives functions, namely:

- Minimizing thermal discomfort in winter and summer,
- Minimize visual discomfort caused by glare and excessive daylight.

Windows' and walls' U-values were also used along with the infiltration rate of the building envelope to minimize the energy consumption of a retrofit building (Murray et alumni, 2014) and alongside properties of solar collectors to minimize the energy use of a building in a cost efficient manner (Asadi et al., 2012). Pernodet et al. 2009, also introduced glazing ratios together with U-values and lighting regulation to minimize the energy consumption. Coley and Schukat, (2002) used thermal conductivity and thermal capacity to minimize the energy consumption of a school building refurbishment in France. In Zhang and others (Zhang et al., 2016) the objective was to define the most optimal configuration type for classrooms and corridor, regarding lighting and thermal comfort. More specifically to minimize energy usage for heating and lighting, to reduce summer discomfort time and to maximize the Useful Daylight Illuminance. Manzan, (2014) carried out on an optimization in an office room with a south-facing window in order to design an optimal fixed shading device, based on minimizing its energy demand. Khoroshiltseva et al., 2016 also explored designs for static shading devices that would reduce glare and maximize thermal and daylight comfort.

Exploration of the design space

After their definition, the ranges of the input variables as well as how these can affect the optimization results, are explored by conducting a certain small amount of experiments. This procedure is carried out in order to improve the performance of the subsequent experiments. A traditionally employed method of achieving it is referred to as One-Variable-At-A-Time (OVAT). This introduces exploring one variable at a time while keeping the others fixed. Even though the input of OVAT is insightful, it lacks efficiency when compared to Design of Experiments (DoE) which studies two or more factors simultaneously (Czitrom, 1999). DoE can determine combination of input variables and their ranges which maximize or minimize the objectives of the optimization. This can be typically visualized by correlation matrices, showing negative or positive correlations between inputs and objectives. There are several methods of sampling the design space, such as Random, Factorial, Orthogonal and others. Ultimately, DoE helps us get a good understanding of the optimization problem by highlighting the sources of variation and provides a good starting point for the subsequent optimization algorithm (esteco, nd).

Algorithm selection

Most algorithms in building optimizations are heuristic, in the sense that they do not guarantee a single and optimum design solution but rather constitute an efficient method that increases the probability of identifying the optimum solution or at least getting closer to it. (Oró 2016). They can be divided in two main categories; Single-objective and multi-objective. Most commonly used are multi-objective ones by 60% (Nguyen et al, 2014). In the multi-line optimization BESO category, many single-objective optimizations are conducted separately, each addressing different energy efficiency subproblems (Z.Tian et. al., 2018). Single objective algorithms such as direct search algorithms use heuristic rules to explore the solution space requiring that the objective function be continuous or near-continuous (Li et al. 2017). The most promising and commonly used category of algorithms used for design optimizations is evolutionary algorithms. They have implementations for both single and multi objective problems. They apply the Darwinian principle of survival of the fittest (Holland, 1975). More specifically, Genetic Algorithms (GA), the most common type of evolutionary algorithms used in multi-objective optimizations, encode potential solutions as chromosome-like data, organizing them in an initial population that undergoes an evolutionary process. The crossover (Goldberg, 1989) and selection (Davis, 1991) operations link older with newer generations while transferring the acquired knowledge. Mutation (Michalewicz, 1996) on the other hand is responsible of providing diversity in the population, to prevent local minima (Xin-She Yang, 2014).

In the context of BESO, every generation is responsible of conducting a simulation and the implementation of the genetic algorithm, after evaluating the simulation's performance based on the objectives, dictates, using the predefined evolutionary processes, the next population. The Multi-Objective Genetic Algorithm (MOGA) was used to identify the interactions between energy cost, retrofit cost and thermal discomfort in a school building (Asadi et al. 2014). In Asadi et al. (2012), different weights for each objective were introduced in the optimization. The Non-sorting Genetic Algorithm (NSGA II) was used by both Carlucci et al. (2015) and Brunelli et al. (2016). Gossard et al. (2013) combined an NSGA II with an artificial neural network for a hybrid method to optimize the thermal performance of a building envelope. The main advantage of GAs, when applied to solve multi-objective optimization design problems, is the fact that they typically generate sets of solutions. The main disadvantage of GAs is their lower speed and the Pareto optimality of the solutions cannot be guaranteed ("Multi-objective optimization", 2019).

ModeFRONTIER, the optimization engine used in this study, features an adaptive genetic algorithm called pilOPT, which offers minimal duration, similar or better results compared to other algorithms and does not rely on user manual configuration before running. As stated earlier, in a typical optimization process, the first phase would concern the exploration of the design space by conducting a DoE. In the case of pilOPT however, this process is done in the early stage of the algorithm, after multiple smart strategies of exploring the design space (esteco, nd). Moreover the adaptive nature of this algorithm, means it can speed up the convergence to optimal solution by adapting the genetic properties of the algorithm(e.g. mutation rate) as the optimization runs.

Analysis tools

Pareto front: The Pareto front is defined as a set of non-dominated solutions. A non-dominated solution is one where no objective can be improved without sacrificing at least one other objective. A solution x' is considered dominated by another solution x if, and only if, x is equally good or better than x' with respect to all objectives. Visualizing the pareto front, by means of the tools offered in all optimization engines, can already lead to informed design decision making.

2.6.4 Conclusions

The ultimate goal of this chapter was to investigate different methodologies that have been applied into previous papers, including software used, which variables and objectives were set, how valuable the results were and finally which were the limitations and recommendations. More specifically, Murray et al. (2014) concludes that a multi-objective optimization would suit better complicated processes like the retrofit of a building. In Carlacci et al. (2015), Carlacci highly recommends the use of optimization techniques that would help effectively explore all the solutions along with the non-intuitive ones in a short time. Pernodet et al. (2009) also suggest the use to the Pareto front to classify the solution. This study also highlighted that the generalization of an optimization method to different building shapes and climate conditions is not a simple task. Khoroshiltseva et al. (2016), concludes that the multi-objective approach is an effective procedure in designing energy efficient shading devices when a large set of conflicting objectives affects the performance of the proposed solutions.

Regarding BESO, Z.Tian et al. (Z.Tian et. al., 2017), in their study Towards adoption of building energy simulation and optimization for passive building design: A survey and a review , conducted a detailed survey to professionals who have been or are potentially users of this method. Automatic adjustment of design variables' values in the process, the fact that BESO tools are embedded with optimization algorithms and the important fact of determining an optimal solution and help decision making, stood out as benefits of adopting BESO methods among others. However, the same survey highlights some hindrances of adopting BESO. More specifically, long calculation time and lack of a standard method stand out. This indicates that there is a need to further

analyse the BESO process and try to speed it up.

BESO can still be utilized however in the early design stage of design to introduce building variables and their factor of importance that are often neglected from designers. Passive design optimization strategies may focus on building components such as roofs, window types etc (Z.Tian et. al., 2018).

Concluding, it should be mentioned that while optimization algorithms are one of the widely explored topics used in various engineering disciplines, they are still rarely applied in architectural design. One of the reasons behind this lack of practice is that architectural problems involve not only numerically expressed performance values but also a number of ill-defined criteria, such as aesthetics, constructability etc. The automated optimization procedures fail to take advantage of designer's expertise, while in architectural design an important role should be given to the learning process of a designer, providing him with knowledge on the trade-offs between various disciplines and performance.

CHAPTER 3

METHOD

3.0 BESO

Problem formulation

The particular BESO study aims to investigate the applicability of such a method into the very much needed design task of the retrofitting process of typical school buildings in Greece through passive design interventions. The study can therefore be seen as an exploration of whether or not, and to what extend can the results of the method and the method itself be useful in the hands of OSK in order to guide in more detail the retrofitting process. A typical classroom-corridor layout is being used as a case study model, tested in the three main climate zones of Greece.

Method workflow

As it was already explained in Paragraph 2.6, Building Energy Simulation and Optimization methods seek to identify optimal designs by conducting a series of simulations and optimizations in order to achieve the given design objective(s).
The main advantage of such a method is that it gives the architect the opportunity to explore all the possible design solutions. The set of optimal solutions offered by this method, i.e. the ones fulfilling the objectives the most, can be ultimately filtered down to the most suitable design, based on additional, case-specific criteria.

The method is organized in three phases:

1. Initially, a pre-processing takes place. The basic goals of this phase are:
    - Setting-up the simulation workflow
    - Evaluating it against the existing condition concerning the case study
    - Validating it
    - The exploration of possible variables
2. Once the simulation model is set, the optimization phase starts by:
    - Defining the optimization objectives and variables
    - Selecting the proper algorithm and number of designs
3. The final step consists of:
    - Analysing the results generated by the optimization step
    - Drawing conclusions

The nature of the undergoing case study, namely the renovation of a typical under performing school building typology of Greece), makes this method a very interesting and useful exploration tool, towards a future where a climate/performance based renovation model takes over the current standardized renovation process.

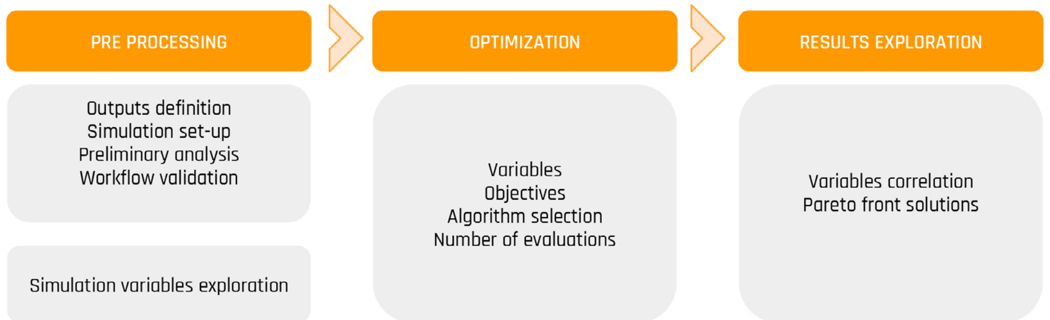


Figure 3.1: Three phases of the BESO method

3.1 Case study

The case study used for this research is a typical classroom-corridor layout. Drawings taken from the 14th Junior High School of Thessaloniki, Greece, represent a very typical example of such school building typology built between the 1960's and the 1980's found all over the country.

Figure 3.2: Photo of the 14th High School building of Thessaloniki, Greece. Source: https://www.facebook.com/oloigiato14/photos/a.496475507105610/2366578630095279/?type=3&theater

Geometry

The school has 3 floors and its front side, where the classrooms are located, faces the south. It consists of a concrete column-beam structural system. Structural grid is 3.6x3.6 m while the free height of the floor is 3.9m. The dimensions of the classroom are 6.9m 7.0m while the corridor has a width of 3.0m, as shown in Figure 8. The wall between the corridor and the classroom is blind while the two facades have a window to wall ratio of approx. 30%. The classrooms usually have a board on one side and approx. 10-12 desks distributed in 3 rows.

Model

The repetitive design nature of the school building, allows for the choice of a representative model which can be met throughout its topology. This model consists of a classroom with part of the corridor, as a cutout of the building. We assume that the results given from this cutout can provide valuable insight for the whole building scale, as the building consists of a repetition of this classroom/corridor units.

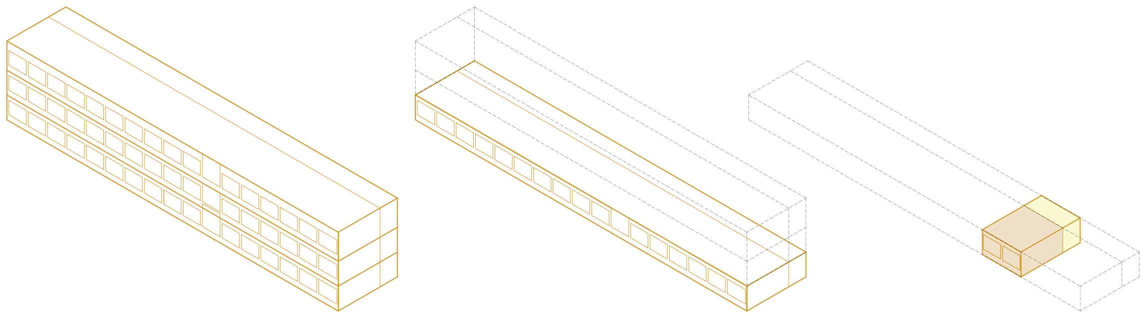


Figure 3.3: The cutout model of the BESO study.

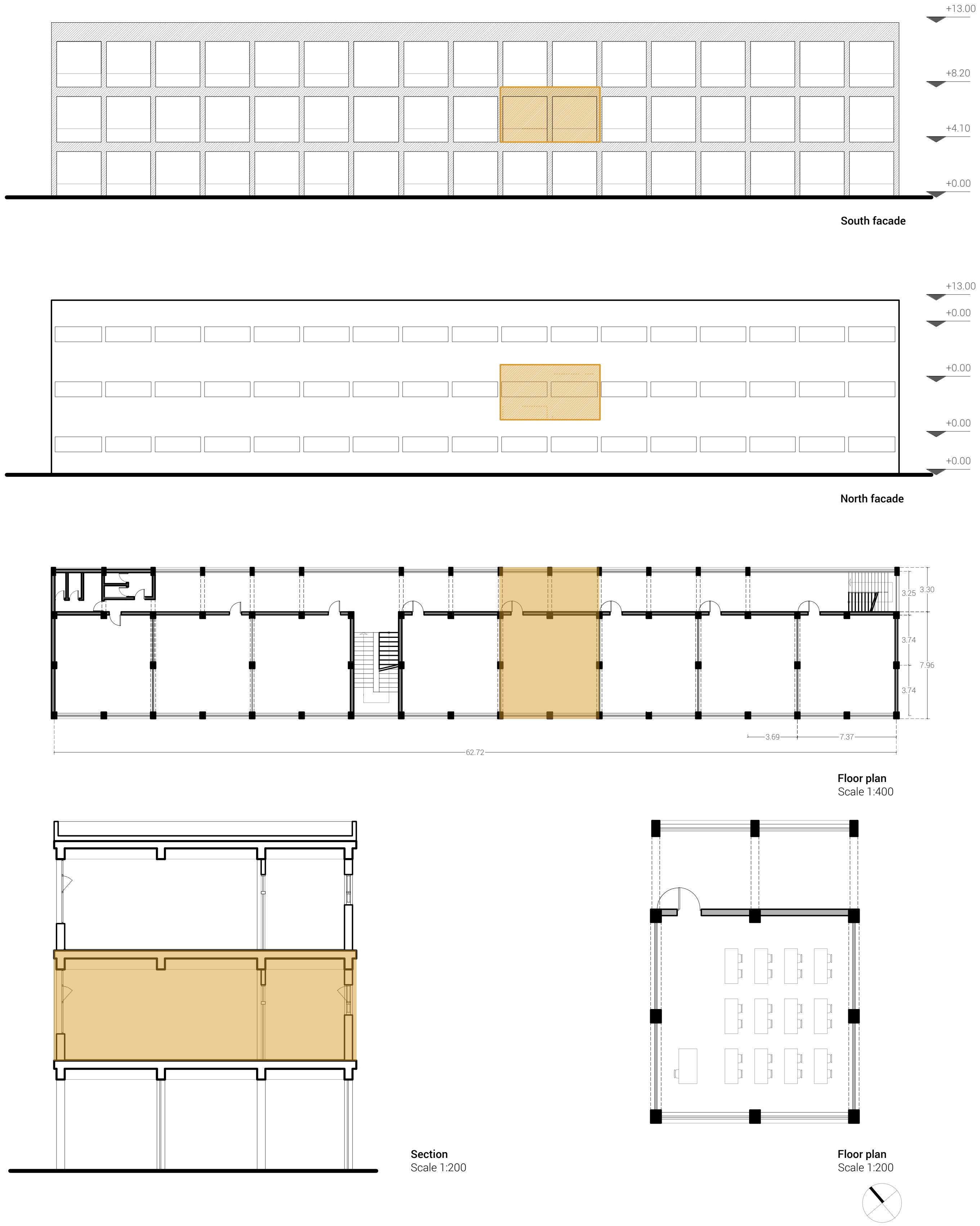


Figure 3.4: Drawings of the 14th High School of Thessaloniki, Greece. Obtained and adapted from the Municipality of Thessaloniki

Materials

The building consists of a concrete structure and brick walls (single ones for interior and double ones for exterior). It is assumed that no wall insulation is in place, which is very often the case for buildings of such an age. Walls are covered with cement stucco and painted in pale colours while floor is covered with PVC. Windows have metal frames and single glazing. Interior curtains are used for sun protection.

All the above along with the rest of input data such as schedules, internal loads etc are described in the Paragraphs 3.3 and are shortly presented in Table 3.1.

Figure 3.5: Interior photos of the 14th Highschool of Thessaloniki, Greece. View of the corridor (above) and classroom (below).

Input information

Geometry

Classroom area: 58m²
Corridor area: 24m²
Free height: 3.9m

Materials

Ext. walls
Double brick walls
(no insulation)
U=1.752 W/m² K

Int. walls:
Single brick walls
U=2.135 W/m² K

Floors/ceilings:
Concrete & PVC
U=5.900 W/m² K

Windows:
Single glazing
U=5.84 W/m² K

Shadings

Interior curtains

Schedules

Occupancy:
Monday-Friday
08:00-16:00
Closed July-August

Required comfort values
(OSK,2008)

Temperatures:
Classroom: 18-25°C
Corridor:16-16-28°C
Lighting:
Classroom: 300 lux
Corridor: 150 lux
Ventilation:
5 ACH

Table 3.1: Input information of the case study model.

3.3 PRE-PROCESSING

3.3.1 Simulation workflow

The simulation workflow takes place in Grasshopper software using Honeybee and Ladybug plug ins. Figure 3.6 shows the steps that need to be followed in order to obtain results for the desired outputs.

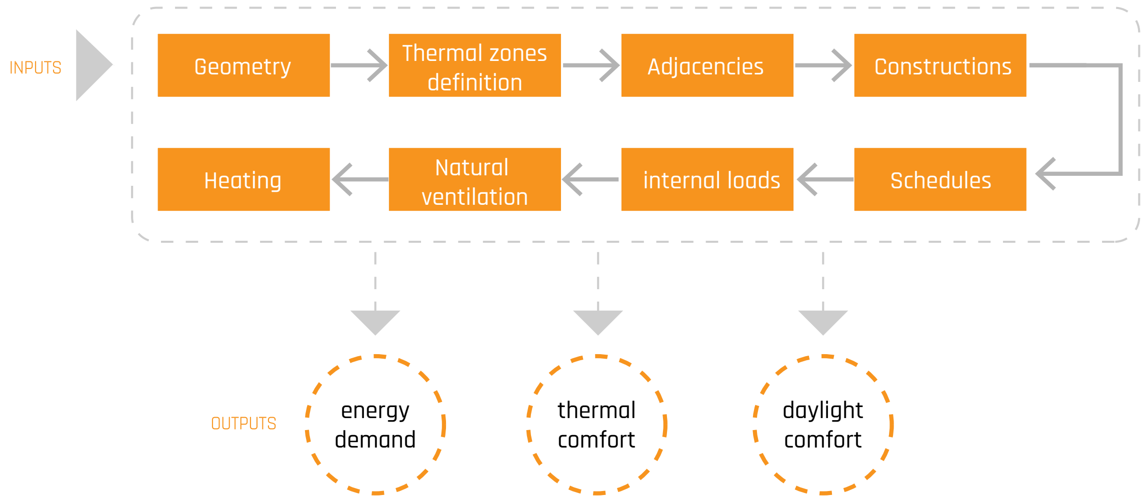


Figure 3.6: Simulation workflow

3.3.1.1 Outputs definition

Every simulation setup starts defining the outputs. In this case, the assessment method of the thermal comfort, energy demand and daylight performance of the model need to be established.

Thermal comfort

The measure for thermal comfort, is described as the percentage of occupancy hours, where the air temperature is within the comfort range specified by the School Building Organization of Greece (OSK). More specifically:

For classrooms the desired temperature is 20˚C , while the comfort range is defined as:

- > 18˚C during winter
- < 25˚C during summer

For the corridors the acceptable comfort range is broader:

- > 16˚C during winter
- < 28˚C during summer

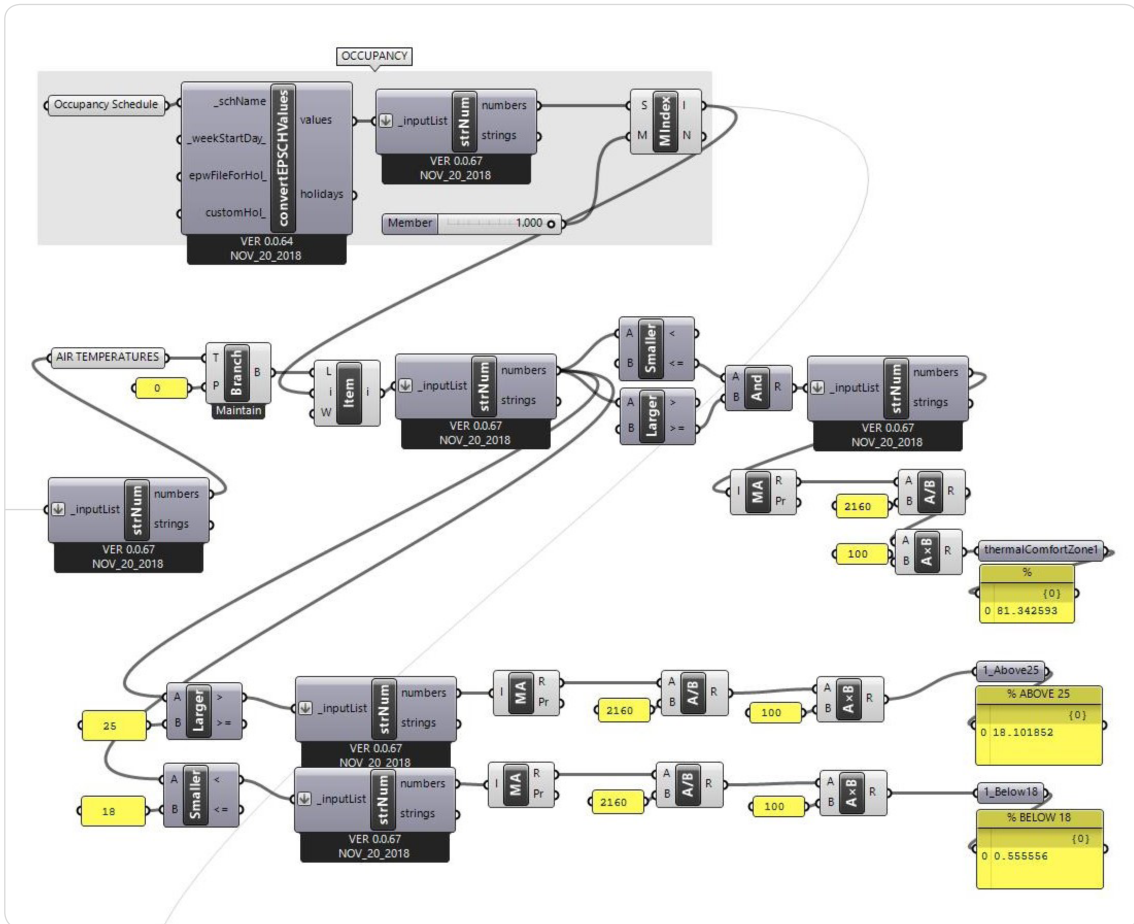


Figure 3.7: Thermal comfort calculation script in Grasshopper.

Energy demand

The energy demand is calculated as the sum of the heating, lighting and electric fan loads. It should be mentioned that no specific HVAC system was used for the simulation. Instead, Ideal air systems are used, which can only however indicate the heat added to the zone by an ideal heating system and not the amount of electricity or fuel that it might take to produce this heat.

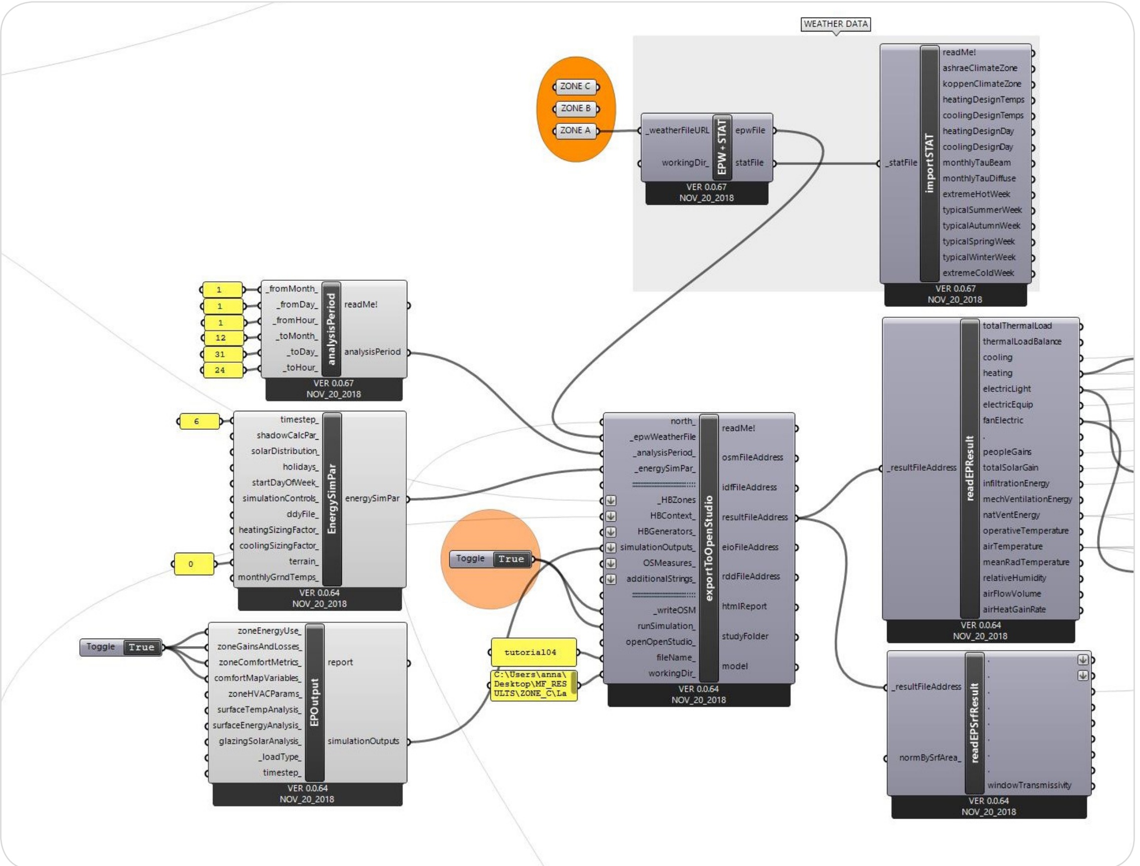


Figure 3.8: Energy analysis script in Grasshopper.

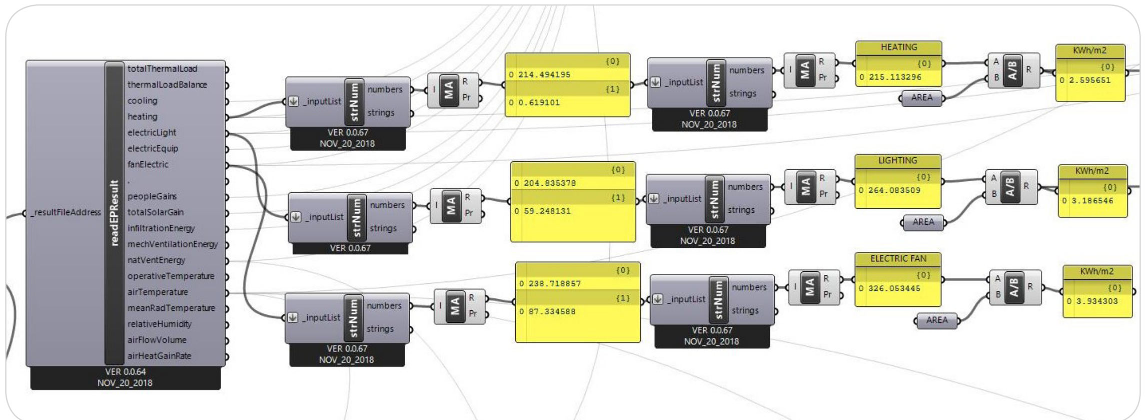


Figure 3.9: Energy demand calculation for heating, lighting and electric fan for ventilation in Grasshopper.

Daylight comfort

Different metrics to assess daylight comfort are provided by the Radiance software. Among those, Daylight autonomy, Useful Daylight illuminance and Spatial Daylight Autonomy (sDA) were initially chosen as the most relevant for this study.

Radiance software provides the following definitions:

- **Daylight Autonomy:** Percentage of the time during the active occupancy hours that the test point receives more daylight than the illuminance threshold (300 lux for this study).
- **Useful Daylight illuminance 100-2000:** Percentage of time during the active occupancy hours that the test point receives between 100 and 2000 lux.
- **Spatial Daylight Autonomy** (sDA) is the percentage of analysis points across the analysis area that meet or exceed a minimum illuminance threshold for at least 50% of the analysis period.

The computational load for running a daylight analysis within the simulation, suggested the need for a trade-off in accuracy, in favour of obtaining meaningful measurements and understanding of daylight behaviour within a reasonable time-frame. Thus a limited number of test points were assigned to the model. As a result, the behaviour and accuracy of sDA, which is heavily affected by spatial density of the test points, was considered sub-par. On the other hand, the minimum threshold of 100lux specified on the illuminance range of UDI, was considered very low in comparison to the 300lux minimum threshold, suggested by OSK. Therefore, in the context of this study, DA was considered the most suitable daylight metric, taking into account the lack of maximum illuminance threshold, over which excessive daylight might cause glare within the zones.

3.3.1.2 Simulation setup steps

Geometry & Thermal zones

The simulation in Honeybee starts with the definition of the thermal zones. In this case two thermal zones are defined, one for the classroom (zone1) and one for the corridor (zone2). The need for this distinction is necessary as different thermal comfort and lighting standards are needed for the two different zones. Moreover, the corridor acts as a buffer zone with greater temperature tolerances.

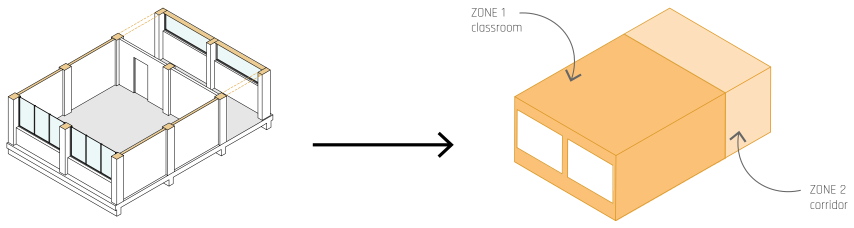


Figure 3.10: Thermal zones of the simulation model

In order to create the thermal zones,the given geometry of the model (given as individual surfaces) is transformed into a honeybee object with assigned building program, as indicated in Figure 3.10. Each individual surface has its own properties, with regards to materials,type, adjacencies etc.

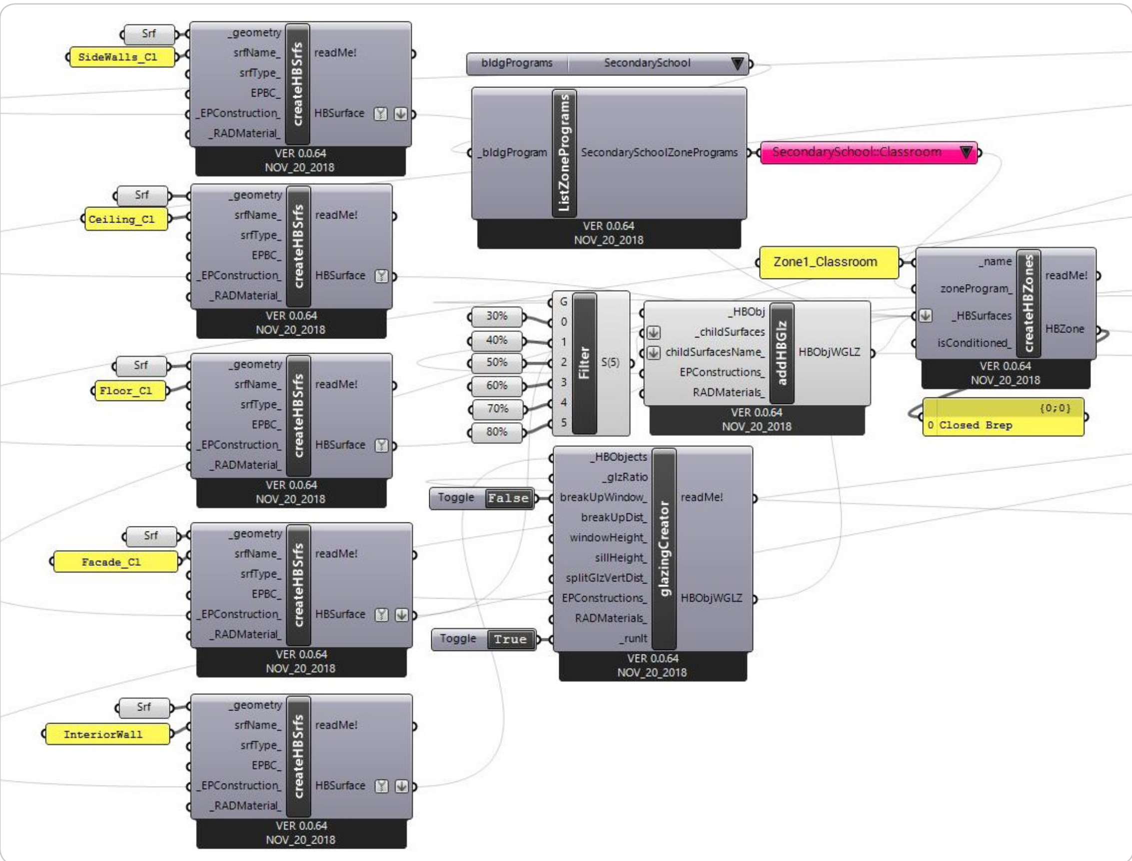


Figure 3.11: Classroom geometry and thermal zone definition script in Grasshoper.

Construction materials

Initially, the construction materials provided to the zones were the ones describing the existing condition of the school buildings and consisted of uninsulated exterior brick walls, single glazed windows, and concrete floors/ceilings. All the material properties can be seen in Table 3.2-3.4.

Material Name	Roughness	Thickness (m)	Conductivity (W/(m²K))	Density (kg/m³)	Spesific heat
0.1M BRICK	Medium	0.1	0.84	1700	800
0.3M CONCRETE	Rough	0.3	2.50	2400	900
0.025M STUCCO	Smooth	0.025	1.40	2100	650
0.025M STUCCO INT.	Smooth	0.025	0.72	1760	840
PVC Flooring	Very smooth	0.003	0.25	1300	880

Table 3.2: Properties of custom materials used for the simulation.

Type	Thickness (mm)	VT	SHGC	U-value (W/m² K)
Singleglazing	6	0.3	0.4	5.84

Table 3.3: Glazing properties used for the simulation.

Construction Name	Layers	U-value (W/m² K)
Exterior brick wall	1. Stucco 0.025m/ 2. Brick 0.10m/ 3. Air cavity 0.05m/ 4. Brick 0.1m/ 5. Stucco 0.025m	1.752
Interior brick wall	1. Stucco 0.025m/ 2. Brick 0.10m/ 3. Stucco 0.025m	2.135
Concrete/PVC floor	1. Stucco 0.025m/ 2. Concrete 0.3m/ 3.Stucco 0.025m/ 4. PVC flooring 0.003m	5.90

Table 3.4: Custom constructions used for the simulations.

Adjacencies

The case study model is a classroom from the middle floor of a 3-floor school building. Therefore the sidewalls, floors, and ceilings are set to adiabatic to prevent heat transfer, which can in turn only occur through the front facades, back facades and the wall separating the 2 zones.

Internal loads

Internal loads include the zones' infiltration rates, lighting intensities and occupancy densities. Initially, when simulating the existing structure, an infiltration rate of 0.0006 m^3/s per m^2 of facade is set for both zones. This value describes a leaky building, since the existing situation introduces quite some leakages due to the old, metal window frames. For subsequent simulations concerning the improved model the infiltration rate is set to 0.0003 m^3/s per m^2. The lighting intensity for both zones is set to 5 W/m^2. Finally, the occupancy density is set to 0.39 people/m^2 for the classroom and 0.11 people/m^2 for the corridor. Values for ventilation per person and ventilation per area were not provided, since no mechanical ventilation is in place.

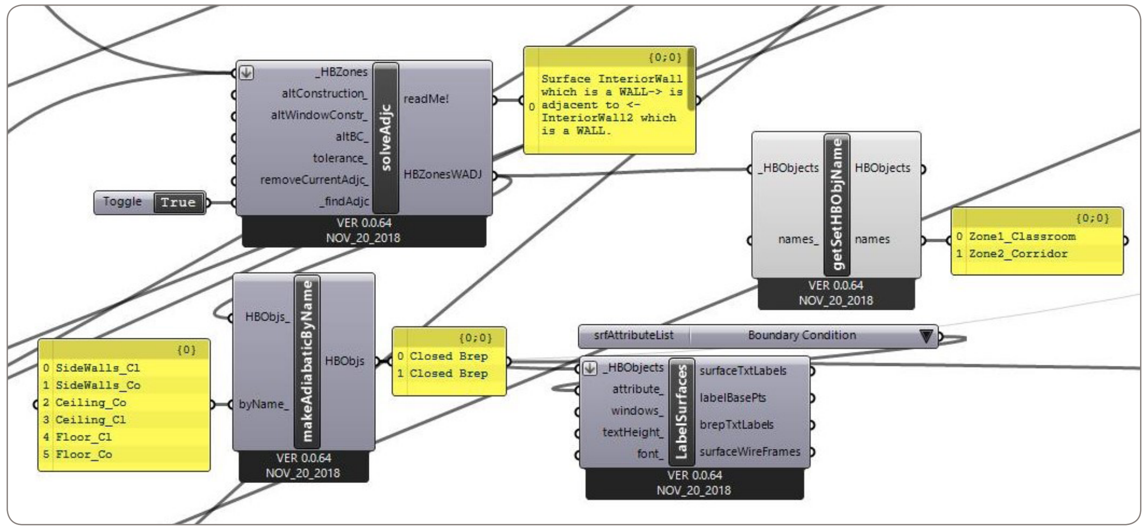


Figure 3.12: Solving adjacencies script

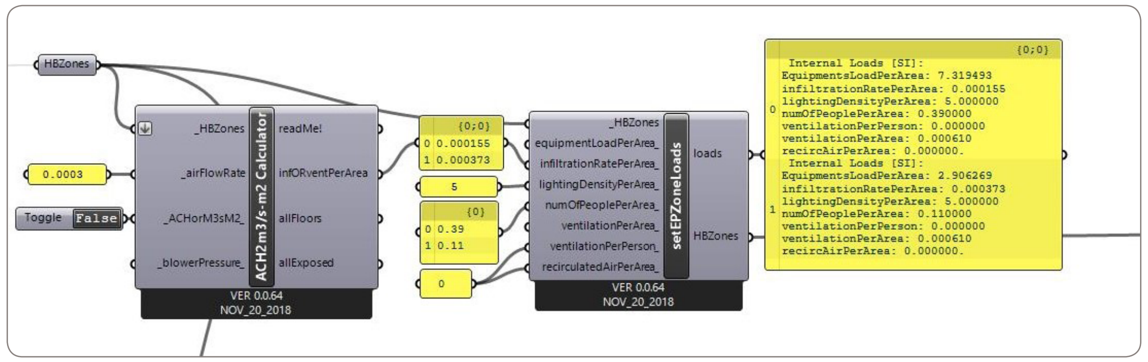


Figure 3.13: Internal loads script

Schedules

The occupancy schedule is set for weekdays, from 07:00 to 17:00, excluding weekends and the months July and August when summer holidays occur. The activity schedule follows the occupancy schedule and introduces a metabolic rate of activity of 108 W/person (Writing/Reading/Sitting) for the classroom and 140W/person (Standing/Walking) for the corridor. The heating setpoint schedule follows the heating availability schedule (November through February during occupancy hours). The heating setpoints were set to 18°Cand 16°C, for the classroom and corridor respectively.

HVAC

The most common way to heat up school buildings built in Greece between the 1960's and the 1980's is through radiators supplied by a central heating system. Resizing and upgrading these old systems using new forms of energy rather than foil is of essence, however implications of and strategies for such actions are not in the scope of this study. Therefore, in the simulation workflow, Ideal air loads provided by EnergyPlus software are introduced, as a way to estimate heating loads without the necessity of providing detailed information and properties of a specific HVAC system. The heating availability schedule is set between November and February. This schedule, although realistic, might fail to cover the real needs of certain schools within climate zone C, where the winter period is often extended.

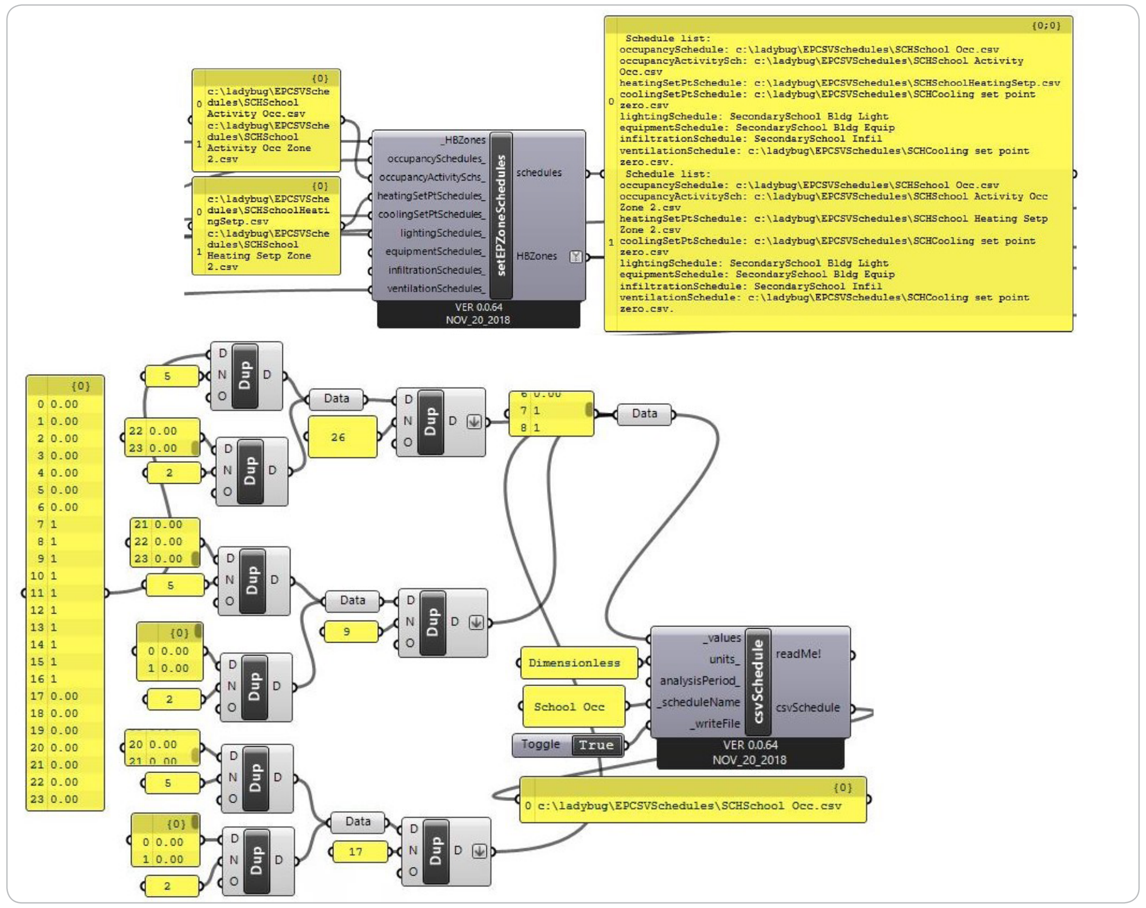


Figure 3.14: Occupancy Schedule script in Grasshopper.

Daylight analysis setup

For the daylight analysis, a test surface is created covering all the area of the classroom, placed 0.8 m above the floor. The test points are distributed along a grid of 1 m, summing up to a total of 49 points.

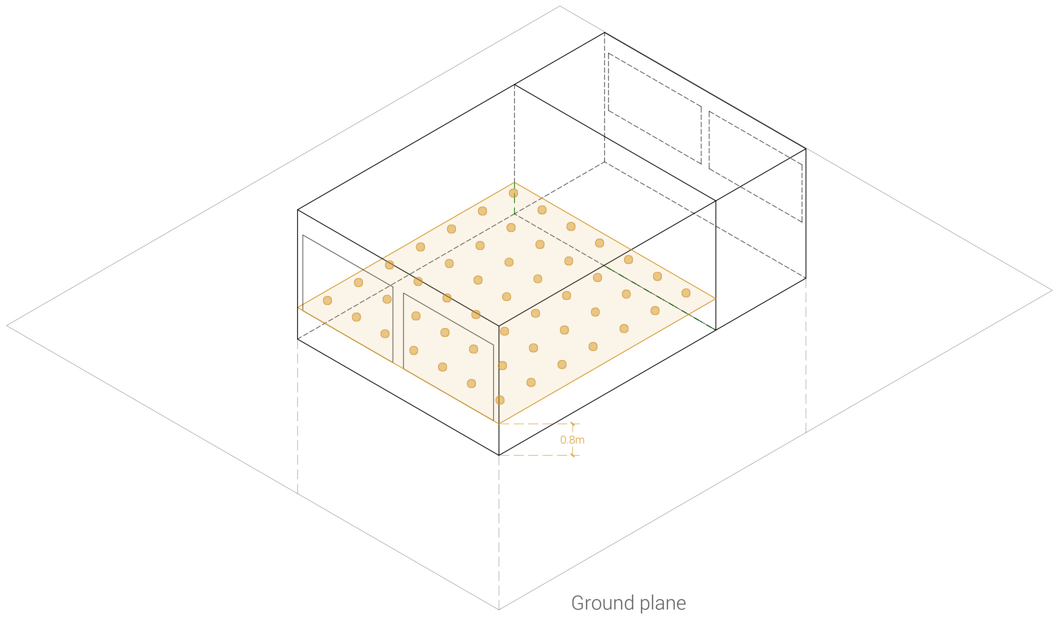


Figure 3.15: Test points given for the daylight analysis

Table 15, shows the RAD parameters specified for the daylight simulation. Similarly to the choice of daylight analysis points, the computational overhead led to a reduced amount of ambient bounces. Other parameters such as ambient accuracy, resolution and super-samples were slightly modified to compensate for the lost accuracy. These updated settings reduce the computational time for up to 80%, while maintaining a satisfactory result accuracy. More specifically, the metric of Avg sDA was equivalent, while the metrics for Avg UDLI and Avg DLA introduced a deviation of 13%.

RAD parameters	Accurate	Very accurate
Ambient bounces	2	5
Ambient accuracy	0.15	0.25
Ambient resolution	128	16
Ambient divisions	512	512
Ambient super-samples	256	128
UDLI 100-2000 lux (%)	**61.21**	**69.64**
sDA (%)	**42.86**	**42.86**
DLA avg(%)	**38.57**	**43.82**

Table 3.5: Results of daylight simulation for different parameters settings.

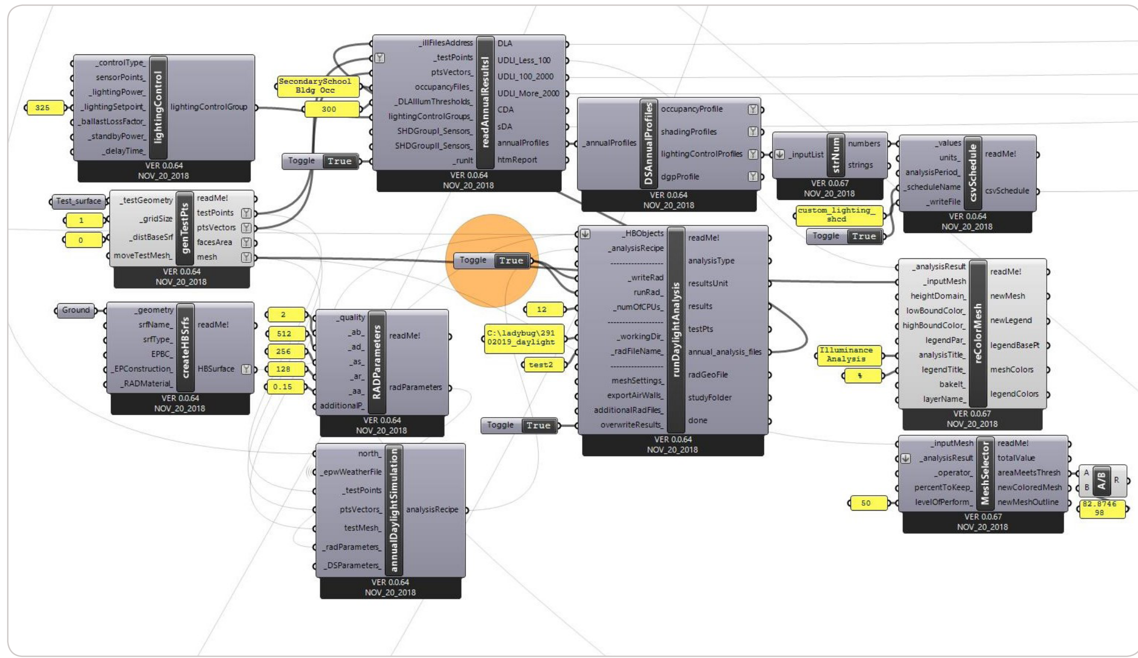


Figure 3.16: Daylight analysis script

3.3.2 Preliminary simulation analysis

The purpose of the preliminary analysis of the existing situation is to gain deeper insights on the current performance of the building under all 3 climate zones, compare the results and ultimately identify the most problematic aspects of each case.

Energy demand

As far as energy demand is concerned (Figure 3.17), we observe an increased value for zone C, as a result of the heating demand needed to address the high, under 18˚C, temperature percentage which is shown in Figure 3.18. Even though the heating demand has increased, the percentage of 'Too cold' hours is still significant. This is possible due to the fact that heating is only available between November and February, meaning that cannot currently fulfil the required comfort conditions throughout the whole cold period.

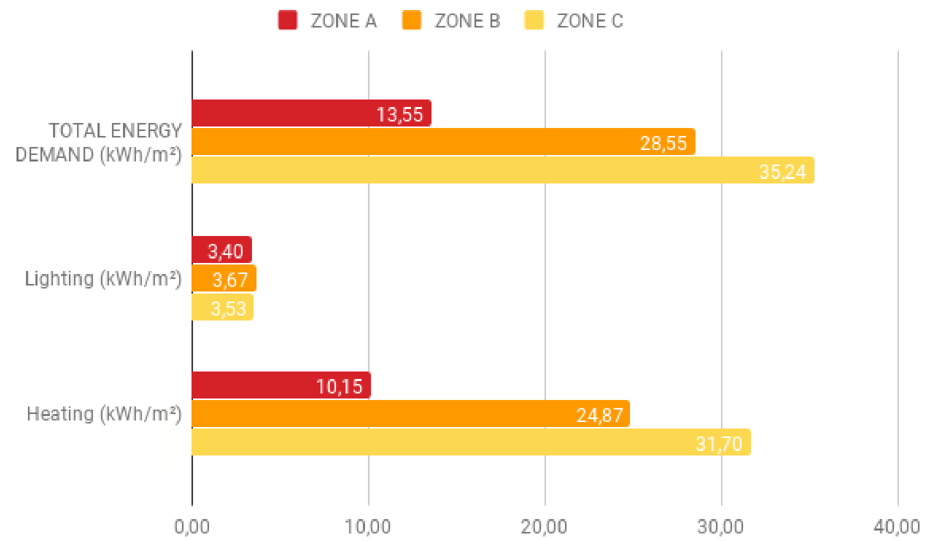


Figure 3.17: Energy demand results of the existing situation for the three climate zones.

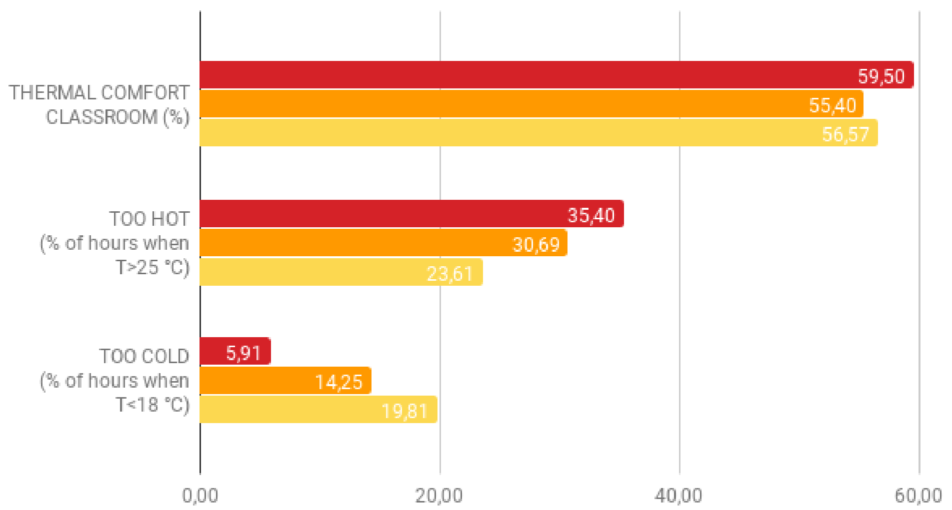


Figure 3.18: Energy demand results of the existing situation for the three climate zones.

Thermal comfort

The Figure 3.19, shows the air temperatures throughout the year for the 3 zones and indicates while their respective out-of-bounds ([18˚C, 25˚C]) hourly recorded temperature percentage for the classroom are shown in figure 3.18. The results indicate increased overheating issues, i.e. percentage of temperatures over 25˚C, for all 3 zones. Moreover, zone C introduces an increased percentage of temperatures under 18˚C.

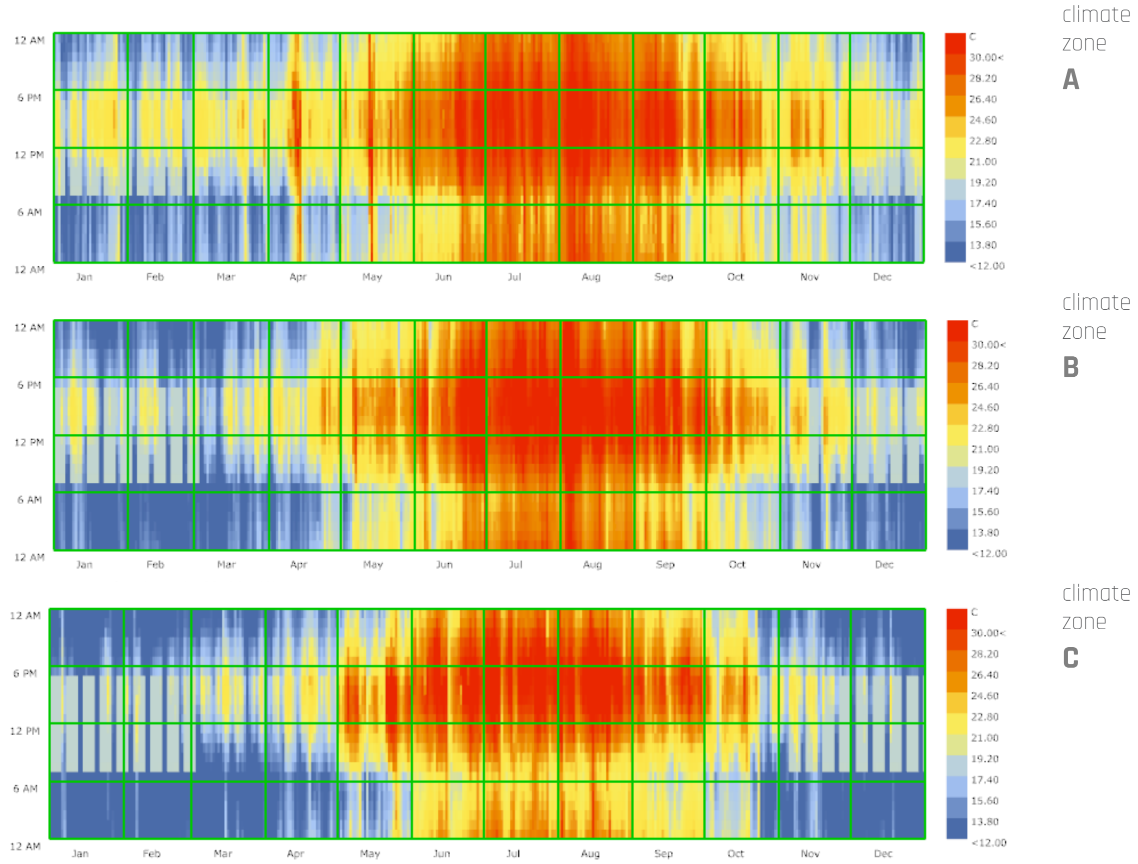


Figure 3.19: Air temperature graphs for the existing model in the three climate zones as exported from Ladybug software using the EPW files described in paragraph 2.3

Daylight comfort

Daylight comfort values are comparable, as expected by the reduced variance in daylight exposure throughout Greece as well as the identical building spaces around the classroom.

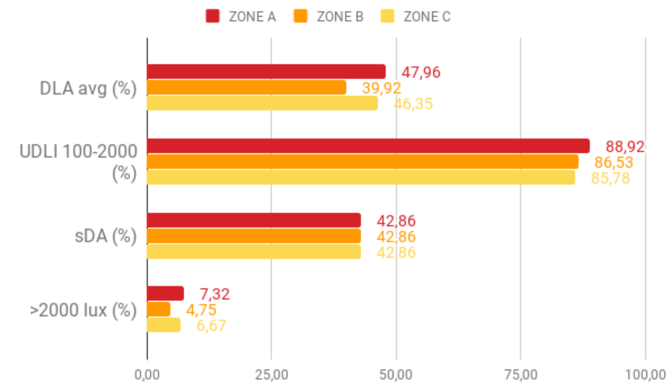


Figure 3.20: Preliminary results for different daylight metrics for the three climate zones, for the existing building.

	SIMULATION OF THE EXISTING SITUATION		
	SOFTWARE	HONEYBEE INPUTS	DESIGN BUILDER INPUTS
CONSTRUCTION	Exterior walls	**Total U-value: 1.752 W/m²K** 1. Stucco 0.0025m/ 2. Brick 0.10m/ 3. Air cavity 0.05m/ 4. Brick 0.1m/ 5. Stucco 0.0 25m	**Total U-value: 1.752 W/m²K** 1. Stucco 0.0025m/ 2. Brick 0.10m/ 3. Air cavity 0.05m/ 4. Brick 0.1m/ 5. Stucco 0.0 25m
	Interior wall	**Total U-value: 2.135 W/m²K** 1. Stucco 0.0025m/ 2. Brick 0.10m/ 3. Stucco 0.0 25m	**Total U-value: 2.135 W/m²K** 1. Stucco 0.0025m/ 2. Brick 0.10m/ 3. Stucco 0.0 25m
	Floor/ceiling	**Adiabatic**	**Adiabatic**
	Glazing	**Single glazing** (U=6.121 W/m²K , VT=0.6, SHGC=0.7)	**Single glazing** (U=6.121 W/m²K , VT=0.6, SHGC=0.7)
	Airtightness (infiltration)	Zone1_Classroom: 0.0006 m3/s per m² Zone2_Corridor: 0.0006 m³/s per m² ON 24/7	Zone1_Classroom: **21,6 m³/h** Zone2_Corridor: **21,6 m³/h** ON 24/7
ACTIVITY	Occupancy schedule	**Monday to Friday 07:00-17:00** (Closed during July and August)	**Monday to Friday 07:00-17:00** (Closed during July and August)
	Occupancy density	Zone1_Classroom: **0.39 people/area**, Zone2_Corridor:**0.11 people/per area**	Zone1_Classroom: **0.39 people/area**, Zone2_Corridor:**0.11 people/per area**
	Metabolic rate:	Zone1_Classroom: **108 W/person** (Writting) Zone2_Corridor: **140 W/person** (Standing/walking)	Zone1_Classroom: 108 W/person (Writting) Zone2_Corridor: 140 W/person (Standing/walking)
	Heating setpoint:	Zone1_Classroom: **18°C** Zone2_Corridor: **16°C**	Zone1_Classroom: **18°C** Zone2_Corridor: **16°C**
DAYLIGHT/ LIGHTING	Power density	5 W/m²	5 W/m²
	Target Illuminance	Zone1_Classroom: **300 lux** Zone2_Corridor: **150 lux**	Zone1_Classroom: **300 lux** Zone2_Corridor: **150 lux**
	Lighting control	On during occupancy hours	On during occupancy hours
HVAC	Heating system	Ideal air loads	Ideal air loads
	Availability	November to February	November to February
NATURAL VENTILATION	Type	Type 3: Fan driven ventilation **Fan flow rate:** 0.33 m³/s for Zone1_Classroom 0.13 m³/s for Zone2_Corridor	Outside air definition method: 1-By zone Outiside air (ac/h): 5,000
	Availability	Min Oudoor Temp: 5 °C	Schedule: 24/7 Min Outdoor Temp: 5°C

Table 3.6: Inputs given for the simulation of the existing situation of the classroom in the two softwares.

3.3.3 Validation of the developed workflow

The aforementioned simulation workflow was in turn implemented on the Design Builder software, in order to evaluate its validity. Open source software such as Honeybee are a great contribution to the scientific community, however the user of such software should be aware of possibly partially or totally unimplemented features. On the other hand, commercial tools such as Design Builder are more likely to be better tested, maintained and supported. Moreover, some user workflows while setting up the simulation differ between the 2 tools. More specifically, Honeybee starts from an 'empty canvas' and the user is the one responsible of providing all the essential components and their respective inputs, discussed in section 3.3.1.2. Not supplied inputs will be replaced by default values that might deviate significantly from the context of the study in hand. On the other hand, Design Builder offers a more methodical and robust workflow of setting up the simulation. Various input parameters are controlled and narrowed down to a choice from a set of presets. Furthermore, its friendly user interface allows for choosing default templates matching the nature of the case study, while conveniently listing all the necessary parameters.

For these reasons, the validation of the workflow against a tool like Design Builder was considered of essence. For this purpose, Honeybee v0.0.64 and Design Builder v6.1.3.008 were used, running the defined simulation workflow for climate zone C. The inputs given for both simulation are shown in Table 3.6.

Software	Energy demand total (kWh)	Lighting zone 1 (kWh)	Lighting zone 2 (kWh)	Heating zone 1 (kWh)	Heating zone 2 (kWh)	Avg air temperature zone 1 (°C)	Avg air temperature zone 2 (°C)
HB	2.911,8	220,35	63,77	1.333,12	1.294,56	19,10	17,49
DB	3.170,6	254,39	59,94	1.659,33	1.196,64	19,90	17,98

Table 3.7: Results obtained by the simulations in the two software

The results obtained by the simulations are shown in Table 3.7. For the calculation of the energy demands, both tools use the EnergyPlus Engine under the hood. In our comparison, both Heating Energy demand calculations were made using an ideal air load system. However, Design Builder, compared to Honeybee, allowed for more detail and straightforward setup of the ideal air load system, thus some additional configuration was provided. This led to some small deviations in the values obtained. As far as the lighting demand and avg temperatures are concerned, the results are considered equivalent and their minor difference do not suggest significant implementation flaws.

3.3.4 Variables definition

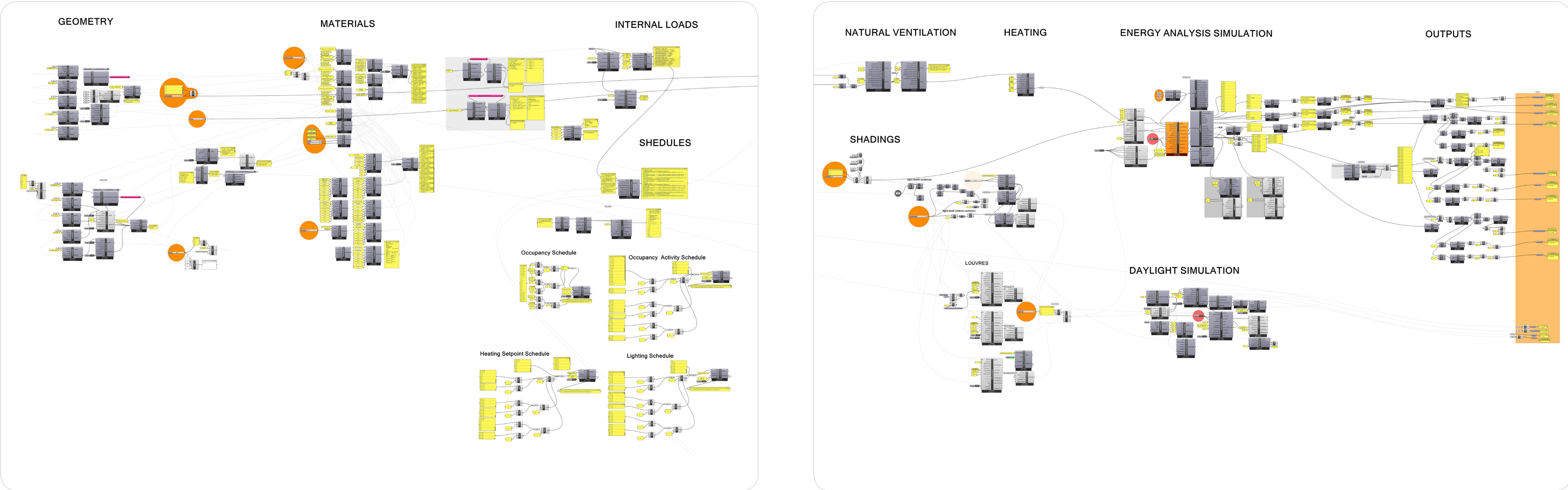


Figure 3.20: Simulation model in GH , Variables are indicated in orange colour.

3.3.4.1 Window-to-wall ratios (wwr)

Window to wall ratios are among the most influential parameters when it comes to passive design, as the size and orientation of openings define to a great extend heat gains or losses and of course daylight comfort. For the classroom model we define three surfaces with parametric glazing areas as it can be seen in Figure 3.21. The main facade of the classroom, which is usually oriented towards south plays the most determining role in classroom's comfort. The wwr of corridor facade is considered an important variable as well, since it allows diffuse light to enter but also north winds to pass through, thus minimizing overheating hours. Attention must be given though because if it does not have sufficient thermal properties it might lead to increased heat losses. Finally, the wwr of the interior wall can have a significant impact as it can bring diffuse light from the north but it can also allow cross ventilation to occur between the two facades.

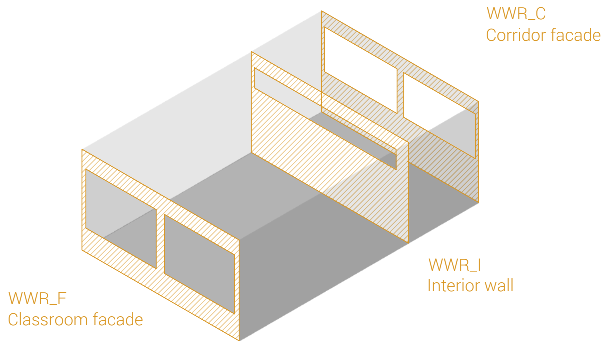


Figure 3.21: The three different surfaces with parametric window to wall ratios

Window-to-wall rations of the front facade is expected to have a great impact on the results due to its south orientation and therefore various ratios are proposed as variables as it can be seen in Figure 3.22. Restrictions were applied regarding of the portions of the opening so that this is integrated in between the existing structure.

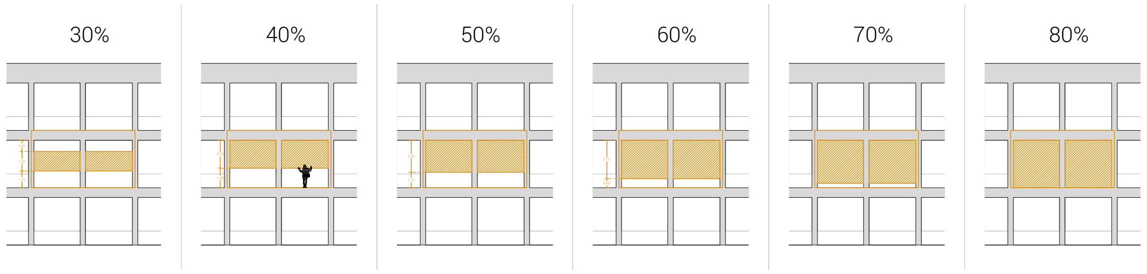


Figure 3.22: Different window-to-wall rations given for the facade, integrated to the existing structure

The window to wall ratios that are given to the interior wall and the corridor facade are the following:

- **wwr_i**: 20%/ 40%/ 60%/ 80%
- **wwr_c**: 30%/ 60%/90% and the option of a semi-open corridor, meaning that the corridor is enclosed by air walls.

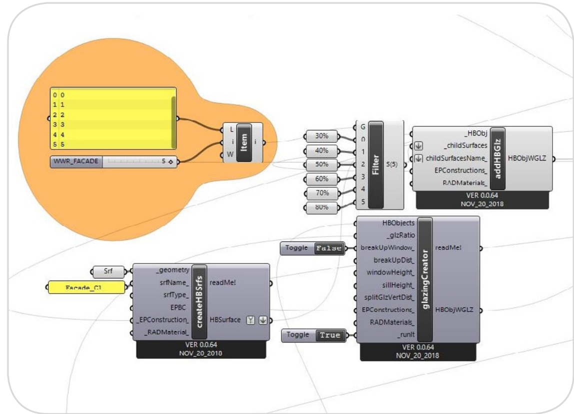


Figure 3.23: wwr_f variable in GH script.

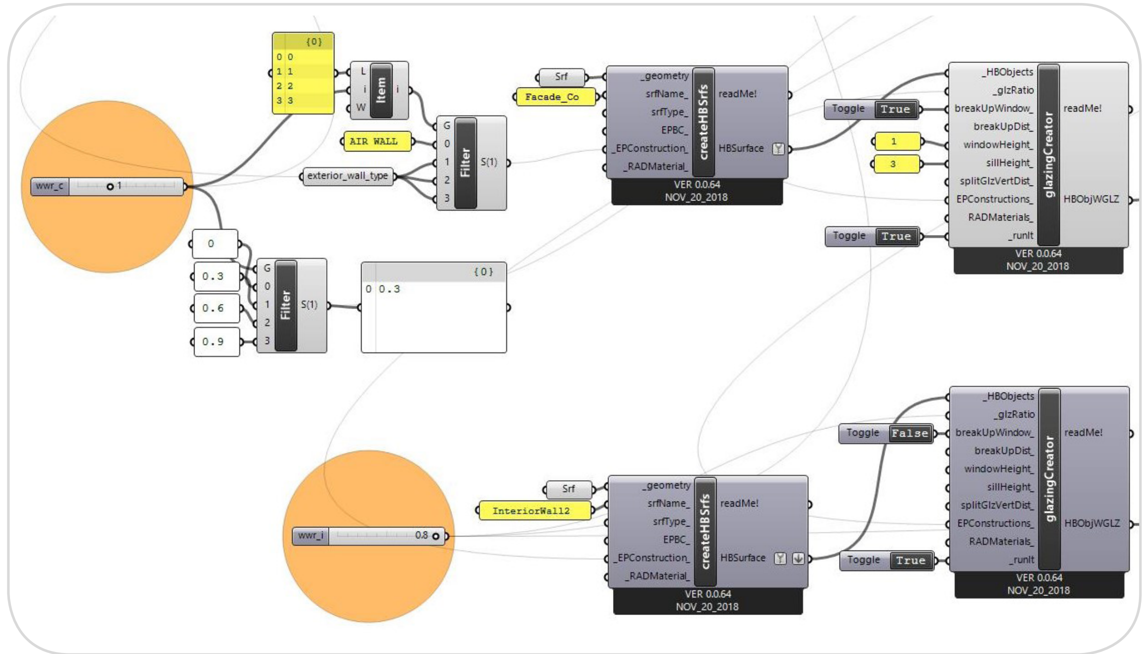


Figure 3.24: wwr_c and wwr_i variables in GH script.

3.3.4.2 Construction materials

Construction materials are assigned to all the surfaces. Several custom wall constructions were explored based on realistic possible material selections and taking into consideration their sustainability aspects and thermal properties. Ultimately, some of the most impactful material properties were chosen as variables while the rest remained constant but still with different assigned values for each climate zone.

Exterior walls

For the exterior walls, an exploration of different insulation materials and configurations took place first, as it can be seen in Figure 3.25 and based on the literature review outcomes. As it turned out though, during the preliminary simulations, there was no significant difference on the thermal performance between the different options and therefore, at this stage of the research, exterior wall construction is not be considered part of the optimization variables. Instead, an improved U-value is assigned to the exterior wall indicating the addition of insulation to the existing situation. The assigned U-value is different for each climate zone, following the minimum requirements that were presented in Paragraph 2.2. More specifically:

- For zone A: U=0.60 W/m² K
- For zone B: U=0.50 W/m² K
- For zone C: U=0.46 W/m² K

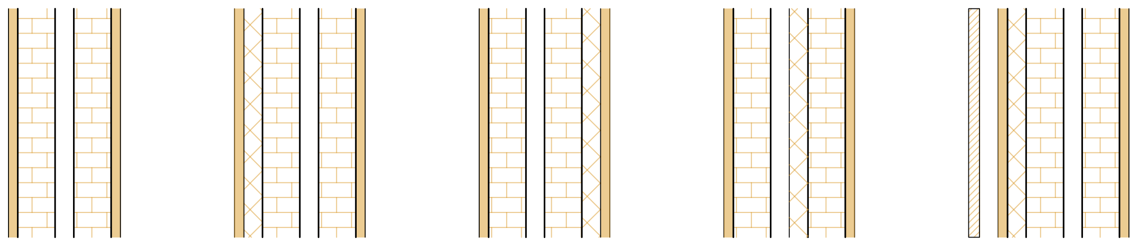


Figure 3.25: Different exterior wall types.

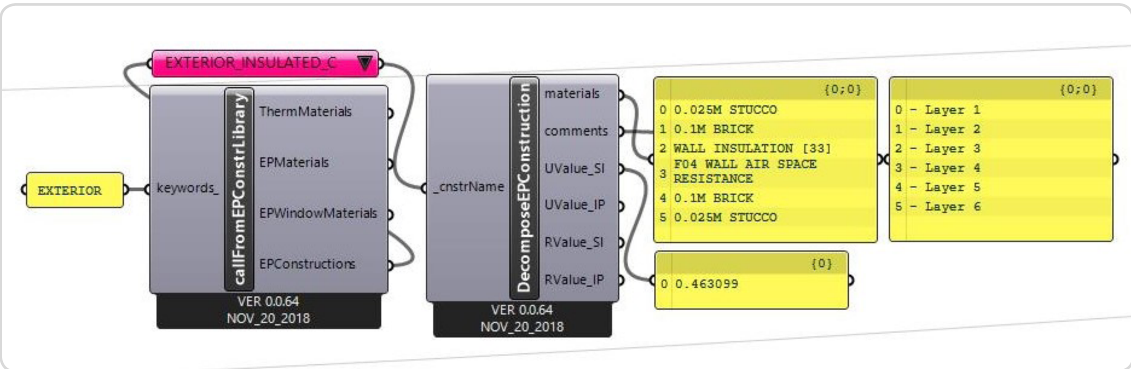


Figure 3.26: Construction of exterior wall for zone C.

Interior wall

Heat transfer between classroom and corridor might be or might need to be different for each climate zone. Therefore, the thermal resistance of the interior wall is considered a variable, with the following possible values:

R_interior_wall: 0.5/ 1.0/ 1.5 m²K/W

Window properties

Regarding the window properties, double glazing is used in the improved model. U value will be considered constant during optimization phase but still with different values for each zone, based on the requirements mentioned in Paragraph 2.2. On the contrary, VT and SHGC will be variables in order to gain more insight regarding their preferred values. The ranges are defined as below, as an outcome of the literature review:

VT: 0.4/ 0.5/ 0.6/ 0.7
SHGC: 0.2/0.3/0.4/0.5/0.6/0.7

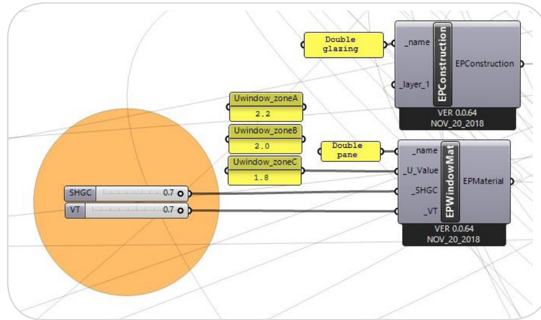


Figure 3.27: SHGC and VT variables in the GH script.

- U_window_A=2.2 W/m² K
- U_window_B=2.0 W/m² K
- U_window_C=1.8 W/m² K

3.3.4.3 Natural ventilation

In Greece, school buildings do not offer an active system for cooling/ventilation. Natural ventilation is the most common way of ventilating and passively cooling down space. It usually happens by simply opening the windows during the breaks while most often it is also enhanced by the use of fans placed in the classrooms.

Regarding regulations, the only requirement provided by OSK is that of 5 air changes per hour for the classrooms. Air changes per hour (ACPH or ACH) measures the air volume added to or removed from a space divided by the volume of the space. Assuming that the air within the space is either uniform or perfectly mixed, air changes per hour is a measure of how many times the air within a defined space is replaced. Translating this demand into airflow rate we would need 0,33m³/s per m².

The conversion between air changes per hour and ventilation rate per person can be done as follows:

$$Rp = \frac{ACPH * D * h}{60}$$

("Air changes per hour", 2019)

Where
Rp = ventilation rate per person (L/minute per person)
ACPH = Air changes per hour
D = Occupant density (square meters per occupant)
h = Ceiling height (meters)

For the specific case study, and based on the 5ach requirement, the ventilation rate per person is calculated to be 15 L/s per person.

In general, modelling ventilation is a complex task but EnergyPlus has many simplifications that do not require much computational time. Nevertheless, attention must be given to the selected type of ventilation for each case study. The types of natural ventilation provided by Honeybee EnergyPlus are the following, as they are described in the component itself:

- Single-sided Ventilation - ventilation driven by the height difference across individual windows on a single side of a building.
- Cross Ventilation - ventilation driven by the pressure difference across windows on two opposite sides of a building
- Chimney Ventilation - ventilation driven by a chimney/stack that is attached to a zone.
- Cowl Ventilation - ventilation driven by wind through a cowl attached to a zone.
- Fan-driven Ventilation - ventilation at a constant flow rate driven by a fan.

Before proceeding with the exploration of the different strategies it is important to define the main purpose of natural ventilation in the specific case study. Natural ventilation is needed to ensure a certain airflow and thus air quality within the classroom (to prevent illnesses etc) but it is also the main way to cool down the building passively by removing the heat once its already there. Depending on the ventilation strategy the simulation model can control and take advantage either one or both objectives. Before choosing the most proper natural ventilation strategy, several scenarios are explored.

The first scenario is creating airflow by transforming the ACH requirement of 5 to an infiltration rate that which is then assigned to the internal loads. This is a very controllable way to ensure sufficient airflow based on the regulation requirements. Though such a scenario could give relatively accurate results in the simulation, it is unrealistic. In addition to that, in this way, natural ventilation is disconnected to other relevant parameters that would affect it in real life, such as opening size or wind speed, and thus it is not preferred.

The second and closer to reality scenario includes wind driven natural ventilation. This can either be single sided or cross ventilation depending on the size of the openings. As a condition for the cross ventilation to occur all the window-to-wall rations of the surfaces (front facade, interior wall and corridor facade) must be equal or greater than 30%. Windows open when interior temperature rises above a certain value while the openable area is half the window area for the classroom side and the whole window area for the corridor side. Several threshold temperatures were explored to determine the ones with the best trade off between energy demand and thermal comfort. Comparing the results for different minimum indoors temperature values for ventilation to occur. There are some interesting observations to be made such as the fact that when MinIndoorTempForNatVent is set to 18°C there is an extremely big heating load. This is reasonable as windows immediately open once the heating set-point which is also 18°C is reached, causing the heating system to immediately turn back on after it has just been turned off, leading to an increased energy demand. In general we conclude that the minimum ventilation temperature has to be at least 2-3 degrees higher than the heating set-point to minimize heating demand while still avoiding overheating. Cross ventilation gives better results than the single sided one, as expected. The drawback of this method though is the fact that it cannot guarantee the desired airflow, so this strategy is mainly acting as passive cooling only.

Fan driven ventilation is the 3rd strategy to be explored, assuming there is an electric fan driving the air flow. This method is considered to be much more controllable than simply opening the windows, but there is also a cost for running the fan itself. Within this simulation only the evaluation of the potential thermal gains of this strategy will be considered as, there is another layer of complexity with calculating the electricity consumed by the fan itself. As a first step the fanFlowRate needs to be determined. This flow rate is meant to be the total outdoor air flow rate in m^3/s that must enter the zone when the indoor temperature rises above the "minIndoorTempForNatVent" and it is not divided by the floor area. In this case 0,33 m^3/s is given as airflow to ensure the 5 air changes per hour.

Finally, the impact of nocturnal ventilation is explored. This is done by assigning a schedule indicating that windows open during night hours for specific months, minimizing overheating hours.

In general, natural ventilation settings proved to be quite a complicated task and with very significant impact on the final results. As an example, when outdoor min temperature for ventilation was explored, it led to very confusing results as the energy demand for heating ended up being twice as big for zone A than zone C which did not make sense as zone C has much colder temperatures. The reason was that during winter months, zone C has exterior dry bulb temperatures lower than 15 degrees almost 50% of the occupancy time. Therefore natural ventilation is not enabled and heating demand is less. On the other hand, the amount of hours below 15 degrees in zone A is very little, therefore natural ventilation is enabled leading to increased heating loads. This led to the decision not to take into account the outdoor temperature as this would demand different settings for each climate zone. Many more similar examples led to misleading results, emphasizing the importance of experience, background knowledge and the need for validation of results.

Ultimately, within the scope of this research, ventilation strategy remains constant for all the three climate zones, based on the following settings:

- Wind driven natural ventilation (windows): MinIndoor=22°C/MinOutdoor=10°C MaxOutdoor=32°C. Cross ventilation is enables when all wwr are above 0.3.
- Fan driven natural ventilation: MinIndoortdoorTemp=18°C (air flow rate 0.33m^3/s)

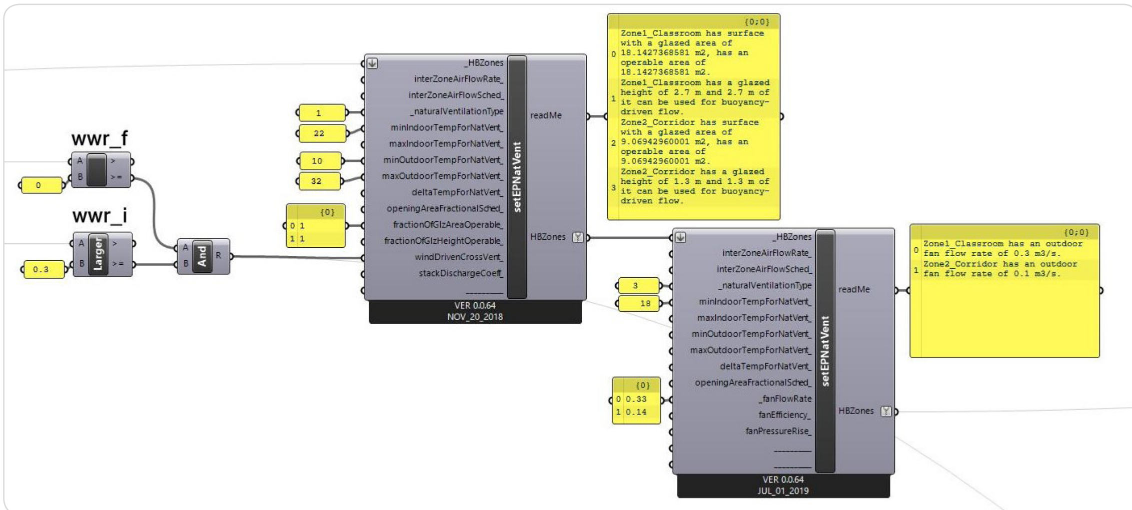


Figure 3.28: Natural ventilation settings in GH

3.3.4.4 Shadings

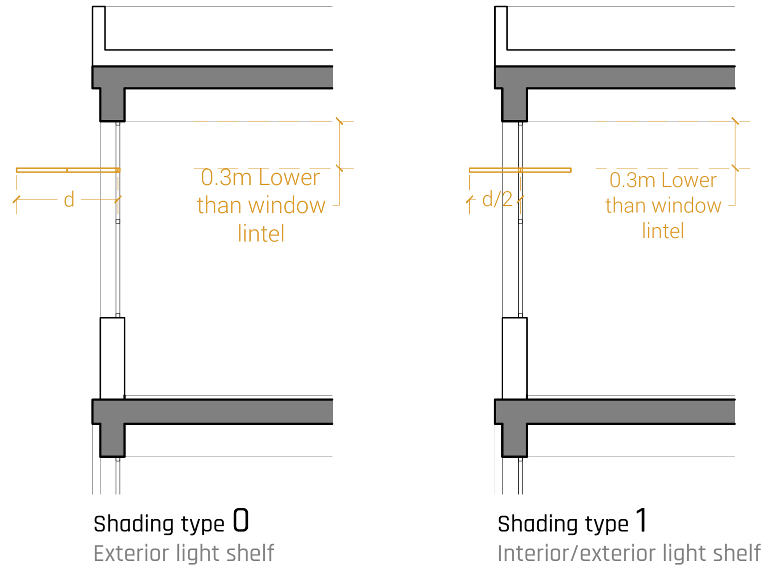


Figure 3.29: Shading types 0 and 1, indicating their properties and variables.

Selection of shadings was a much more straightforward process. As it came out from the literature review, exterior shading elements are the most preferable as they prevent the solar radiation heat entering the space, offering better protection against overheating. Interior shadings such as venetian blinds or clothes are most commonly used supplementary to offer protection against glare if needed, but within the scope of this study they are not taken into account. The proposed exterior shadings are permanent elements which are more affordable and need less maintenance compared to the dynamic ones. Due to the orientation of the classrooms which is mainly towards south (or south-east or south west), the proposed shading types are mainly horizontal with only one option being vertical. All the shading options can be seen in Figure 3.29 and 3.31. The light shelves are modelled with a parametric depth and reflectance values while horizontal and vertical louvres adapt to windows height. Regarding the shading through vegetation option, a density of 40% is given.

Conducting a preliminary analysis for different shading types, we notice that although reflectance plays an important role in the effectiveness of shading devices, ensuring diffused distribution of light, in this case it does not affect the results at all and therefore will not be considered as a variable for the optimization. This is explained due to the ambient bounces settings, given in the daylight analysis, which are not enough for the reflections to be calculated. Therefore, only the light shelf depth and the type of shading are ultimately kept as variables. (Indicated in orange colour in Figures 3.30 and 3.32).

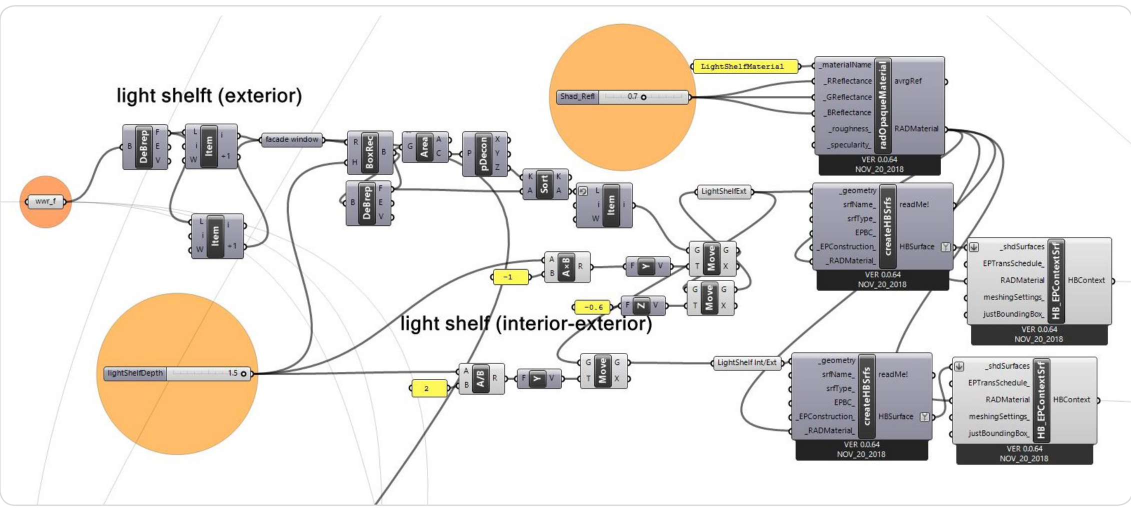


Figure 3.30: Light shelf types in the simulation model.

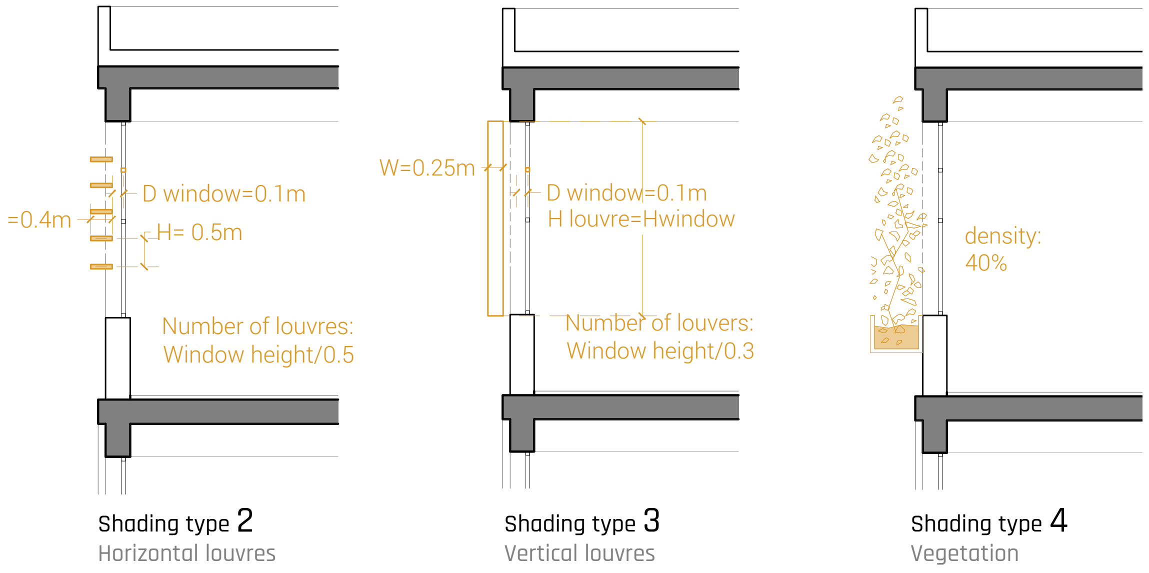


Figure 3.31: Shading types 2,3 and 4, indicating their properties and variables.

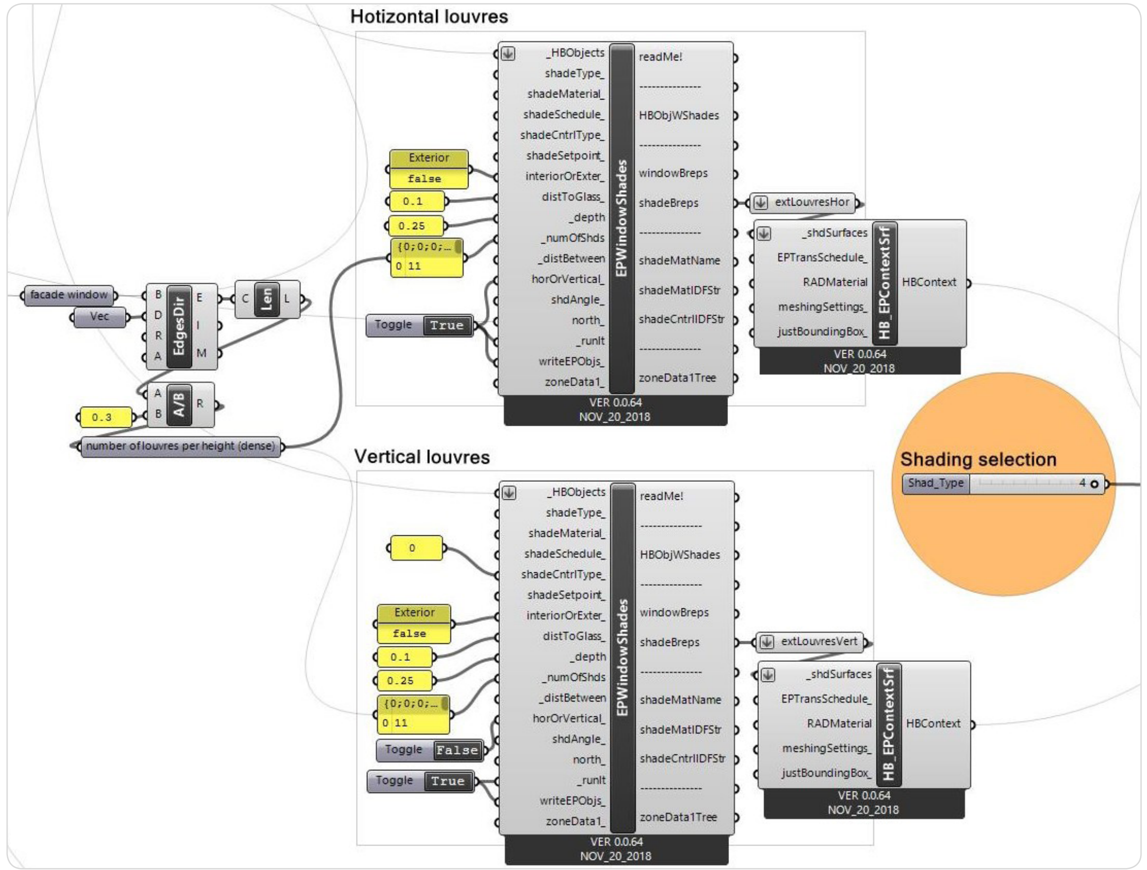


Figure 3.32: Horizontal and vertical louvres as shading types in the simulation model in GH.

3.3.4.5 Orientation

It is obvious that when it comes to retrofitting processes, orientation cannot act as a variable. Nevertheless, as it came out from the literature review, orientation can have a great impact to both solar heat gains and shading type selection. The most optimal way to explore the influence of orientation with regards to the other variables and objectives would be to run more optimizations, given different orientations for the different climate zones. In this way though, the required optimizations would be at least 9 for this research and not possible within the time line. The decision was that to integrate orientation as variable within the optimization, aiming to identify correlations with the rest of the variables and not to seek optimal orientations.

Most existing school buildings in Greece are oriented towards South. Depending on the plot orientation os shape though this can often be south-east or south-west. Consequently, the proposed orientation values for the optimization are presented in Table 3.8.

Value	Orientation
0	South
1	East
2	West

Table 3.8: Orientation values given for the optimization.

3.4 Optimization

3.4.0 Introduction

Within the scope of this research, 3 optimization runs will be presented and further analysed, representing the three main climate zones of Greece. These optimizations were the outcome of many more that were previously attempted, analysed and altered.

For the optimizations, modeFRONTIER 2019R3 software was used. The software offers a custom node which connects the optimization engine to Grasshopper software. In this chapter, the workflow set up is presented, including the definition of variables, objectives and constraints for each optimization.

3.4.1 Optimization workflow setup

The workflow setup takes place in modeFRONTIER's Workflow Editor which acts as a graphical user interface for structuring the design problem and managing its logical steps. The purpose of the workflow is to integrate the simulation software, in this case Grasshopper, with modeFRONTIER and define the inputs, outputs and objectives. Nodes are used as "building blocks" to represent the integrated simulation software (i.e. Grasshopper node) but also all the data exchanged by the two software (input and output variables) as well as the objectives and constraints of the problem, while dashed lines are used to connect the nodes and indicate the direction of information exchange (modeFRONTIER User Guide, n.d).

Through the scheduling Start node, the optimization algorithm is selected. For similar case stud-

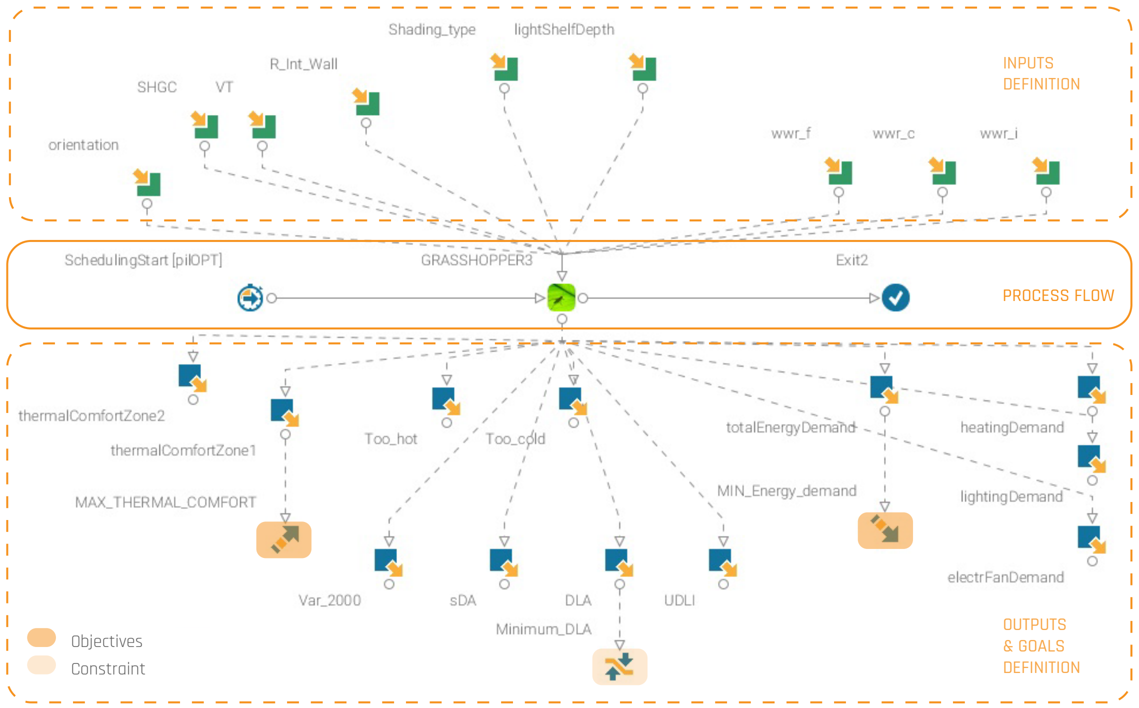


Figure 3.4.1: Optimization workflow in modeFRONTIER.

ies, the most commonly used optimization algorithms are genetic or evolutionary algorithms, and more specifically the MOGA-II or NSGA-II. modeFRONTIER however features an adaptive algorithm called pilOPT, which offers minimal duration, similar or better results compared to other algorithms and does not rely on user manual configuration before running. In a typical optimization process, the first phase would concern the exploration of the design space by conducting a Design Of Experiments(DOE). This procedure can further limit the variables' ranges, ultimately reducing the time cost of the implementation. In the case of pilOPT however, this process is done in the early stage of the algorithm, after multiple smart strategies of exploring the design space. The only input to the algorithm was the number of iterations. In order to determine an approximate minimum number of evaluations, an empirical formula is used based on which the correct number of evaluation is:

2 * number of inputs * number of objectives * 15 generations (modeFRONTIER User Guide, n.d)

which were round to 600 designs. The choice of a minimum number of evaluations was a trade off in possible result quality, in favour of less computation time.

3.4.2 Variables

Each of the optimization runs included 9 variables, leading to 414720 possible combinations. All the variables together with their ranges are presented in Table 3.9.

	OPTIMIZATION VARIABLES							
	Category	Variable	Abbreviation	Optimization Range	Step	Type	Simulation range	Units
1	**Envelope**	WWR facade	wwr_f	[0,5]	1	Discrete	[0.3/0.4/0.5/0.6/0.7/0.8]	-
2	**Envelope**	WWR corridor	wwr_c	[0,3]	1	Discrete	[0/0.3/0.6/0.9]	-
3	**Interior wall**	WWR interior wall	wwr_i	[1,4]	1	Discrete	[0.2/0.4/0.6/0.8]	-
4	**Exterior glazing**	Visible transmittance	VT	[4,7]	1	Discrete	[0.4/0.5/0.6/0.7]	-
5		SHGC	SHGC	[2,7]	1	Discrete	[0.2/0.3/0.4/0.5/0.6/0.7]	-
6	**Shadings**	Shading type	Shading	[0,4]	1	Discrete	Refer to Table 3.10	
7		Light shelf Depth	lightShelfDepth	[6,15]	3	Discrete	[0.6/0.9/1.2/1.5]	m
8	**Orientation**	Classroom Orientation	Or	[0,2]	1	Discrete	0: South/1:SE/2:SW	-
9	**Interior wall material**	R Interior Wall	R_int_wall	[1,3]	1	Discrete	x 0.5	K m²/W

Table 3.9: Optimization variables.

Shading types	
Value	Type
0	Ext. light shelf
1	Ext./int light shelf
2	Hor. louvres
3	Ver. louvres
4	Vegetation

Table 3.10: Shading types.

3.4.3 Objectives & constraint

The main objective of this thesis is to investigate passive design parameters for improving the thermal comfort while at the same time minimizing the energy demand and maintaining adequate daylight comfort.

As a direct consequence, the following two objectives were defined for the optimization:

- Maximize Thermal Comfort of zone 1 (Classroom).
- Minimize Total Energy Demand.

The DLA Aavg was set as constraint of a lower limit of 50%, of at least 300lux illuminance for the classroom.

CHAPTER 4

Optimization Results

4.0 Introduction

In this chapter, the analysis of the results is being presented. The results are analysed for each climate zone separately, starting from Zone A. The analysis is done using the graph analysis tools provided by modeFrontier software. During the exploration of the resulting design space the following main aspects are being examined:

Variables correlations: Correlations between input variables and objectives are examined in order to gain a deeper understanding on the impact of each variable towards the objectives but also identify the most impactful combinations of variables.

Pareto front: Finally the evaluation of the optimal design solutions takes place. Optimal solutions are part of the Pareto front. The Pareto front is defined as a set of non-dominated solutions, if no objective can be improved without sacrificing at least one other objective. A solution x' is considered dominated by another solution x if, and only if, x is equally good or better than x' with respect to all objectives.

Optimization convergence: The convergence of the designs towards achieving the defined objectives as well as the convergence values of the input variables is examined.

More specifically, the analysis includes the following steps:

- General overview of the design spaces, looking into the overall distribution of the designs with regards to the objectives, the achieved ranges of values with regards to the objectives, the number of feasible designs based on the defined constraint etc.
- Analysis on the impact of each variable towards the different outputs and exploration of possible combinations of variables.
- Identification of the Pareto Front designs, highlighting the ones with the best performance.
- Conclusions in the form of guidelines.

4.1 Results: ZONE A

The optimization took 29 hours to perform the 600 designs, out of which 56 are unfeasible meaning that they did not meet the minimum DLA avg value of 50%, leading to 544 feasible design options. The distribution of the designs with regards to the two objectives can be seen in *Figure 4.1*. The range of thermal comfort percentages is between 75-82% while energy demand varies between 6-18 kWh/m².

414720 possible combinations | **600** design iterations | **29** hours duration | **544** feasible solutions | **28** *Pareto Front* designs

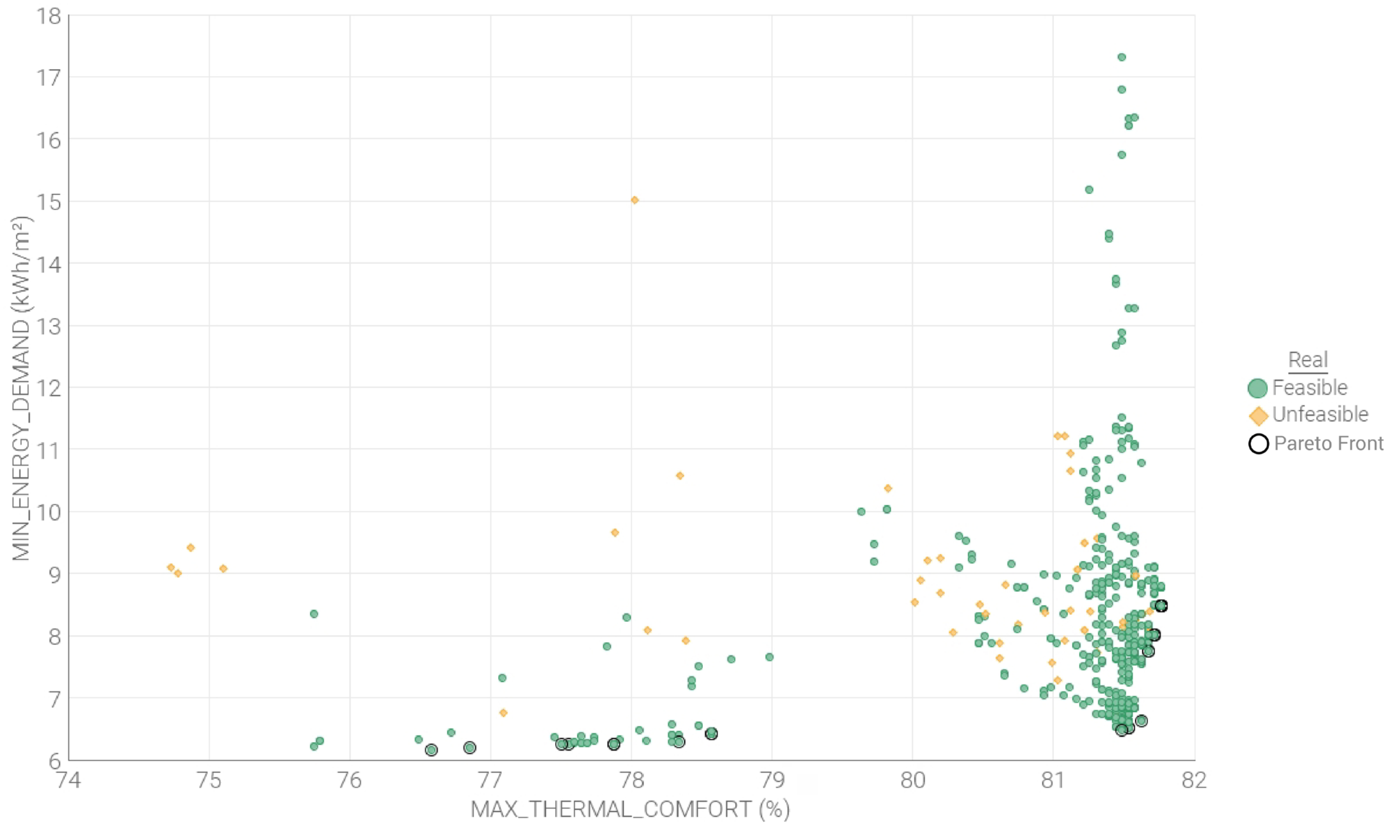


Figure 4.1.1: Design space solutions with their respective objective values for Thermal comfort and Energy demand.

Looking at the design space solutions (Figure 4.1.1) and the evolution of the optimization (Figure 4.1.2) we notice a fast convergence towards high thermal comfort values (close to 82%) while retaining relatively low energy demand values, between 6-8 kWh/m². Nevertheless, there is a large number of Pareto Front designs (indicated with black outline) that do not fulfil the best values with regards to the objectives.

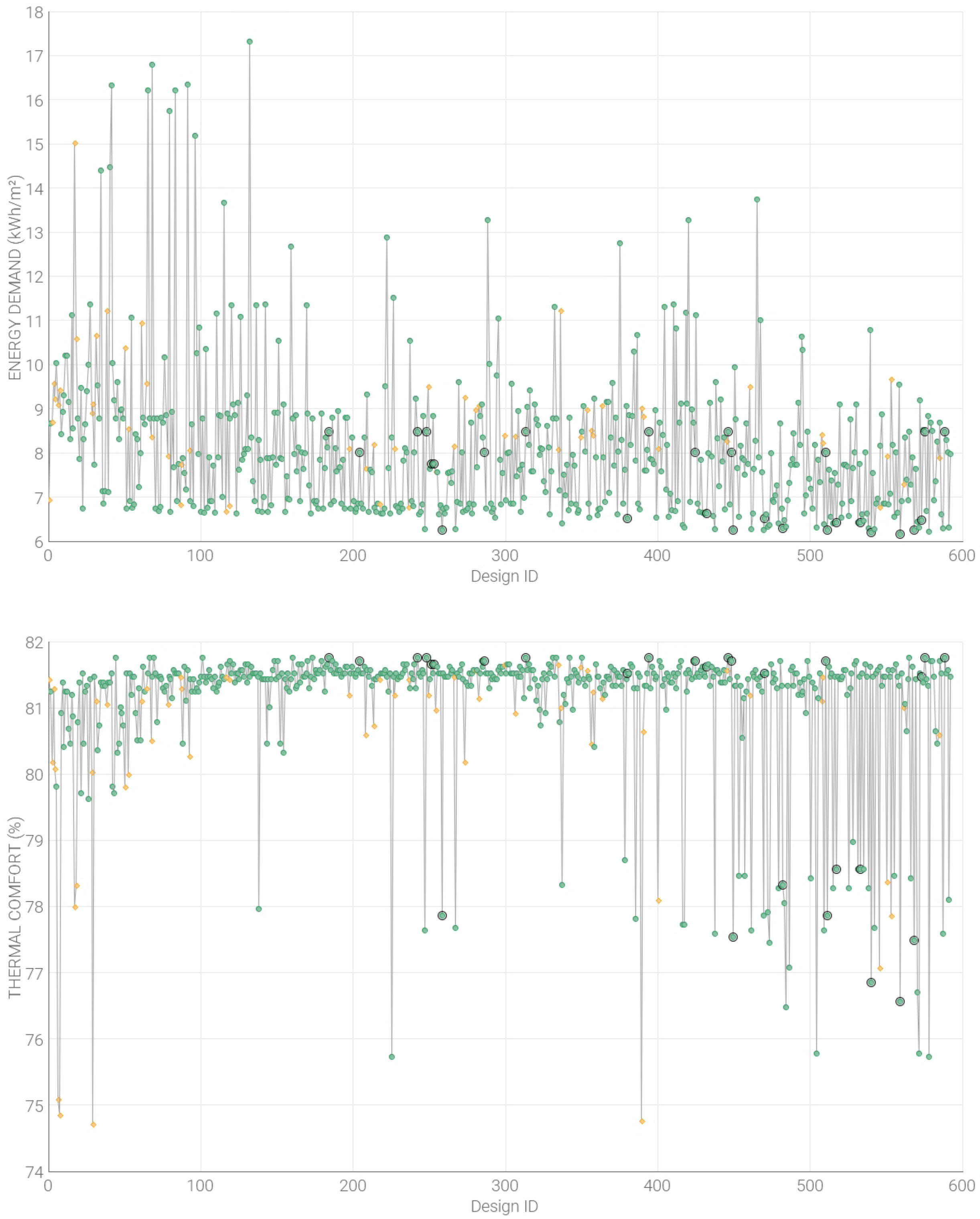


Figure 4.1.2: Convergence of the optimization in relation to the two objectives: Minimize energy demand (above) and Maximize thermal comfort (below)

In order to gain a deeper understanding of the impact of each variable towards the objectives, all the variables are analysed one by one.

4.1.1 Window-to-wall ratios

Looking at the Pearson Correlation chart (Figure 4.1.3) between the different window-to-wall ratio values we identify some first interesting correlations. Wwr_f, appears to have a significant positive correlation to the overall thermal comfort of the classroom and the biggest negative correlation to the percentage of 'Too cold' hours, meaning that higher wwr_f values lead to smaller percentage of 'Too cold' hours. Among all, wwr_i has the greatest correlation to the thermal comfort of the classroom, by reducing the number of 'Too hot' hours, as indicated by the negative correlation between the two variables. Finally, wwr_c, as expected, has the highest impact on the thermal comfort of the corridor.

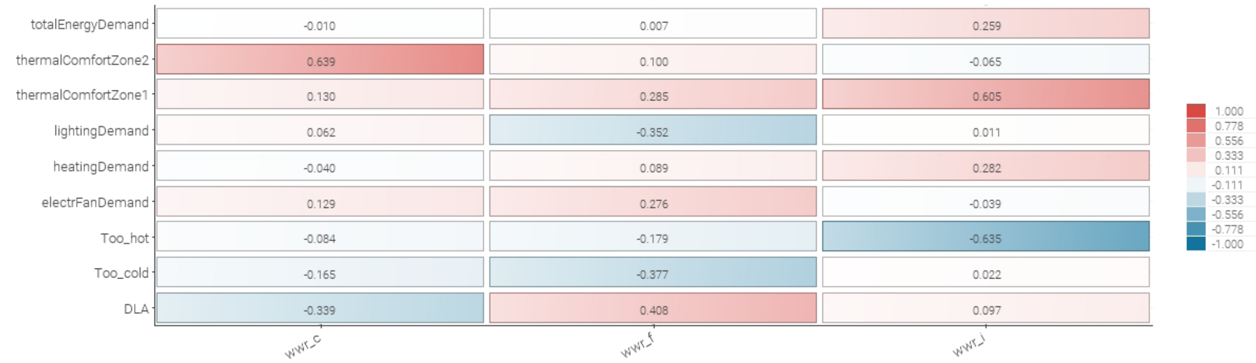


Figure 4.1.3: Pearson correlations between the different window-to-wall ratios and the objectives

wwr_f

The most preferable wwr_f values are clearly the higher ones (wwr_f=0.8) as it appears in Figure 4.1.4, showing the distribution of wwr_f values with regards to the given objectives. In fact, for 460 out of the 600 design solutions, the algorithm chose those highest values. Looking at the correlations between the wwr_f and the rest of the outputs we observe that increased wwr decreases both out-of-bounds temperature percentages, thus improving the thermal comfort. In addition to that we notice a slightly negative correlation with the energy demand, indicating that higher wwr_f values satisfy both the objectives.

Such an observation causes surprise since we would expect lower window-to-wall ratios to be preferred for such warm climate zone that suffers from overheating problems. To gain a deeper understanding of why such high values are preferred or whether there are other factors that lead to their selection, we are looking for correlations between these high wwr_f values and the rest of the variables.

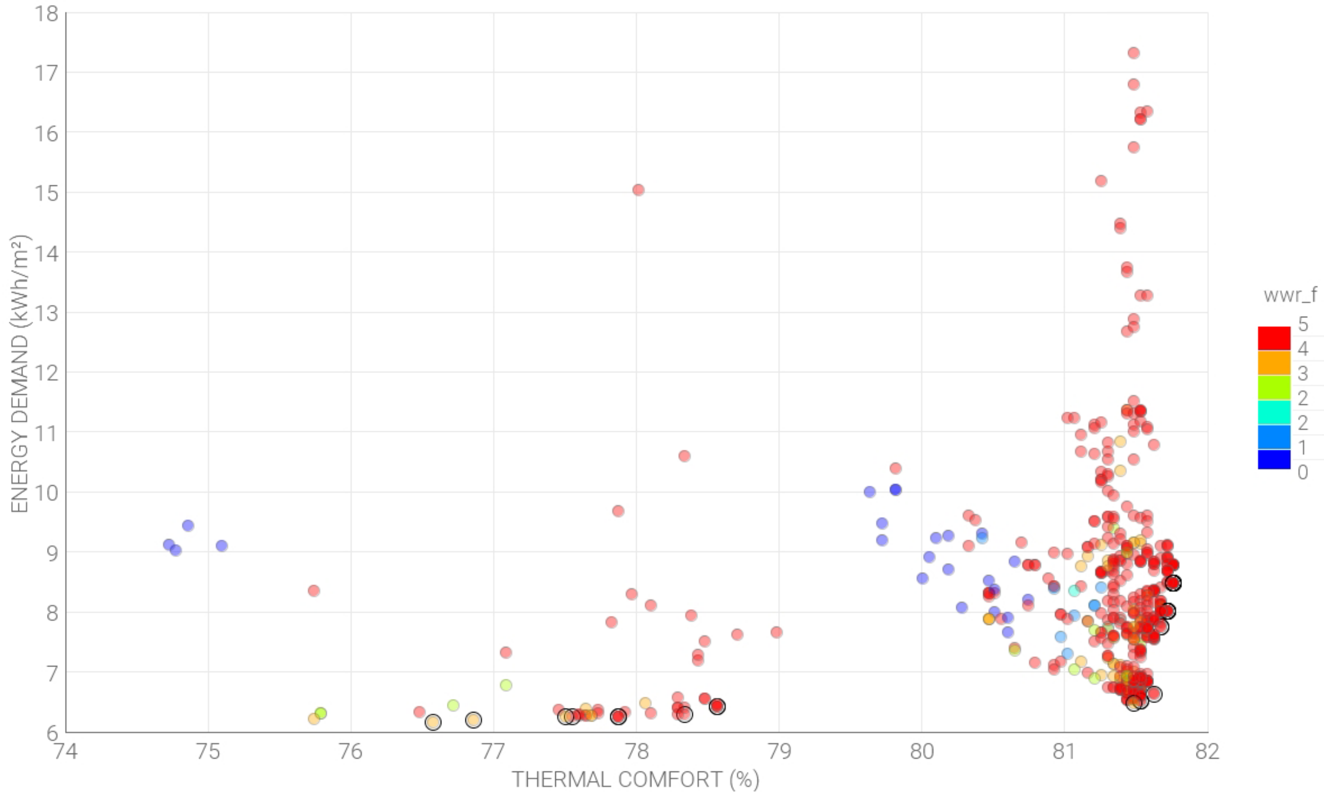


Figure 4.1.4: wwr_f values distribution with regards to Thermal comfort and Energy demand values

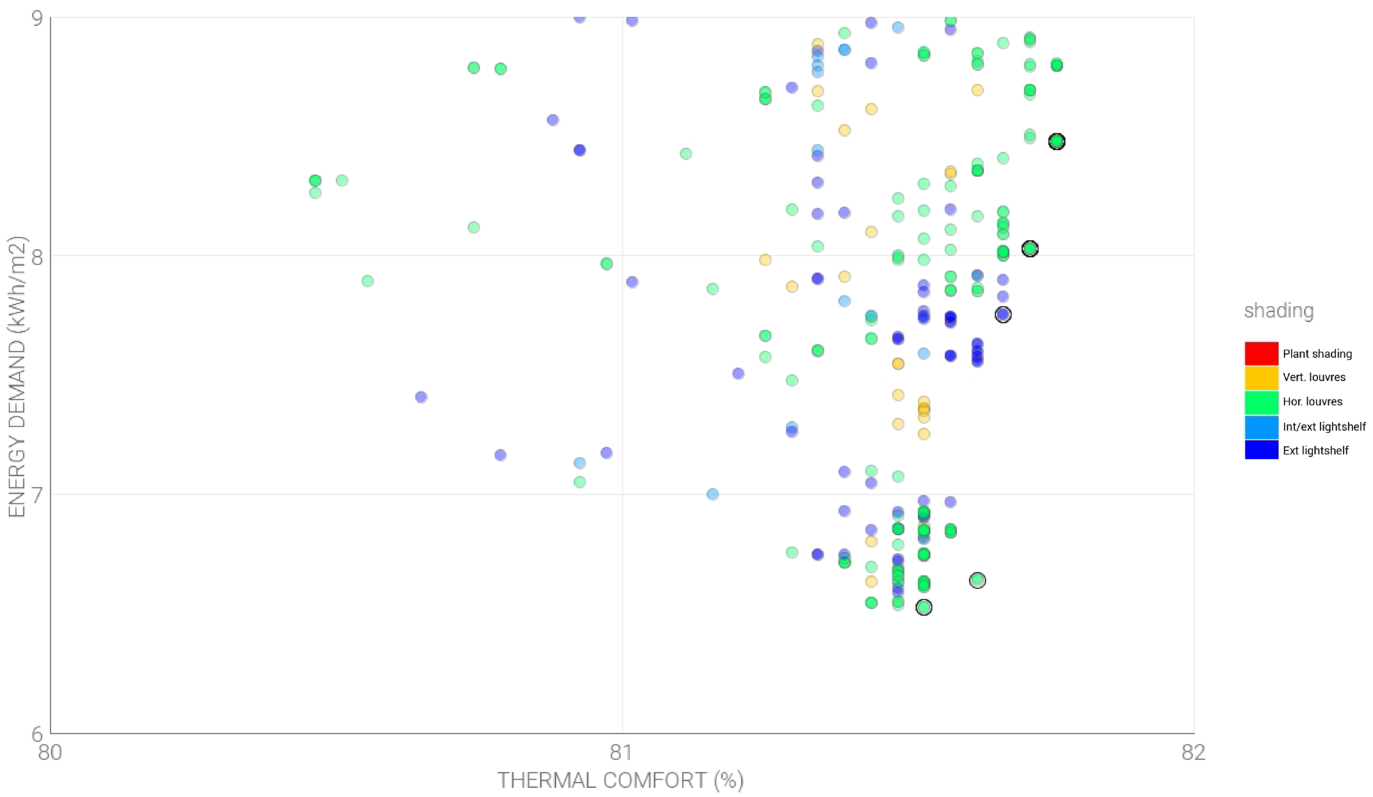


Figure 4.1.5: Shading type values distribution with regards to Thermal comfort and Energy demand values for wwr_f=0.8

Looking at the shading type distribution for the highest wwr_f values, (Figure 4.1.5) we notice that the most preferable types are the horizontal louvres followed by the exterior light shelf with the biggest length (1.5 m) confirming the need for sun protection, while high wwr_f values combined with less effective shadings (such as smaller light shelves) lead to decreased thermal comfort.

wwr_c

Regarding the wwr_c, it appears that the 'open corridor' option (wwr_c=0) leads to the minimum thermal comfort. On the contrary, the preferred values that are also dominant at the Pareto Front solutions are mainly those of 0.3 (Figure 4.1.6).

As indicated in Figure 4.1.7 such values also lead to decreased heating demand which is the most determining factor of the objective of minimizing the total energy demand. Therefore, even though such values slightly increase the electric fan demand, they are still more efficient.

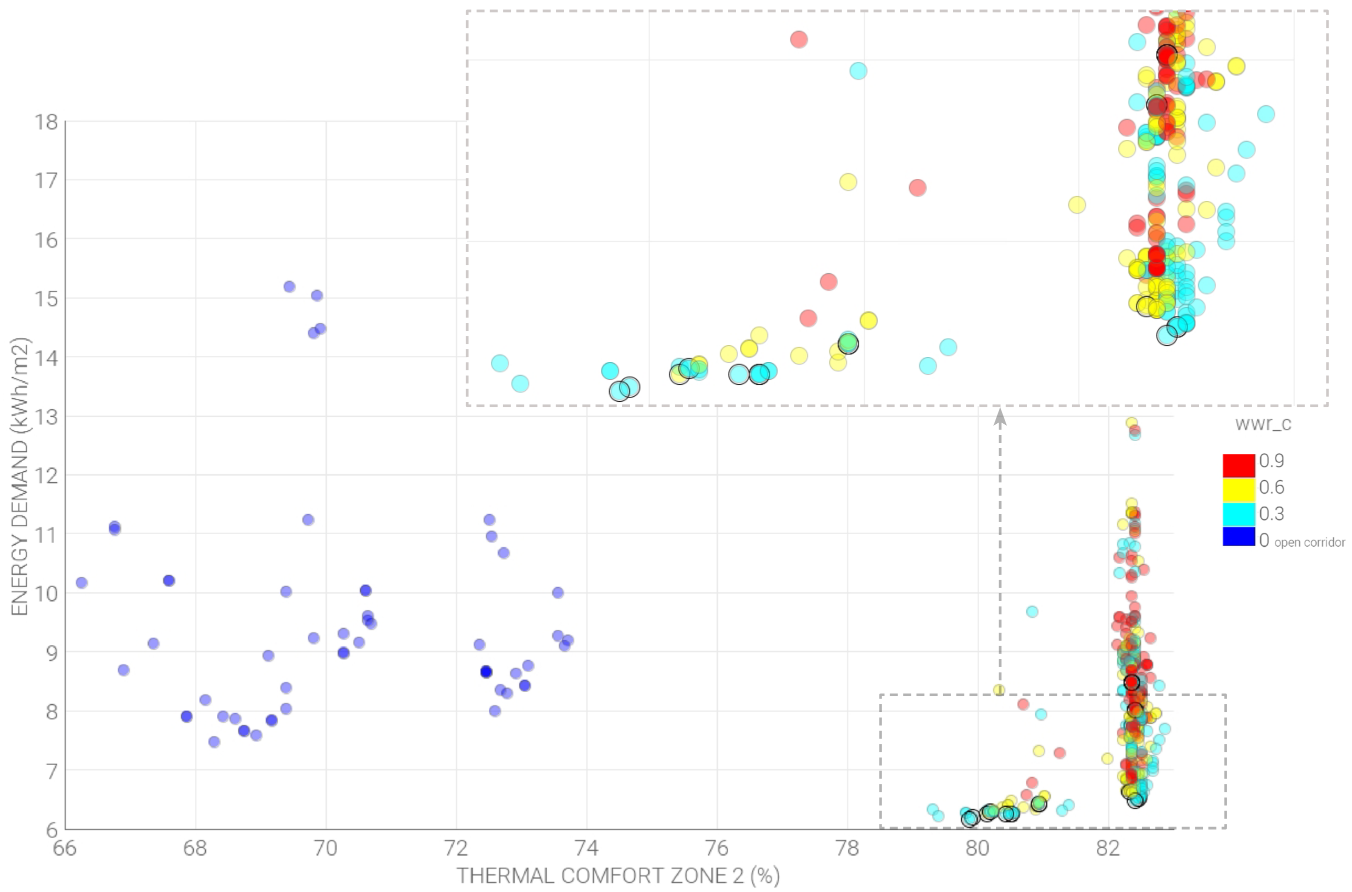


Figure 4.1.6: wwr_c values distribution with regards to Thermal comfort of zone 2 and Energy demand values for wwr_f=0.8

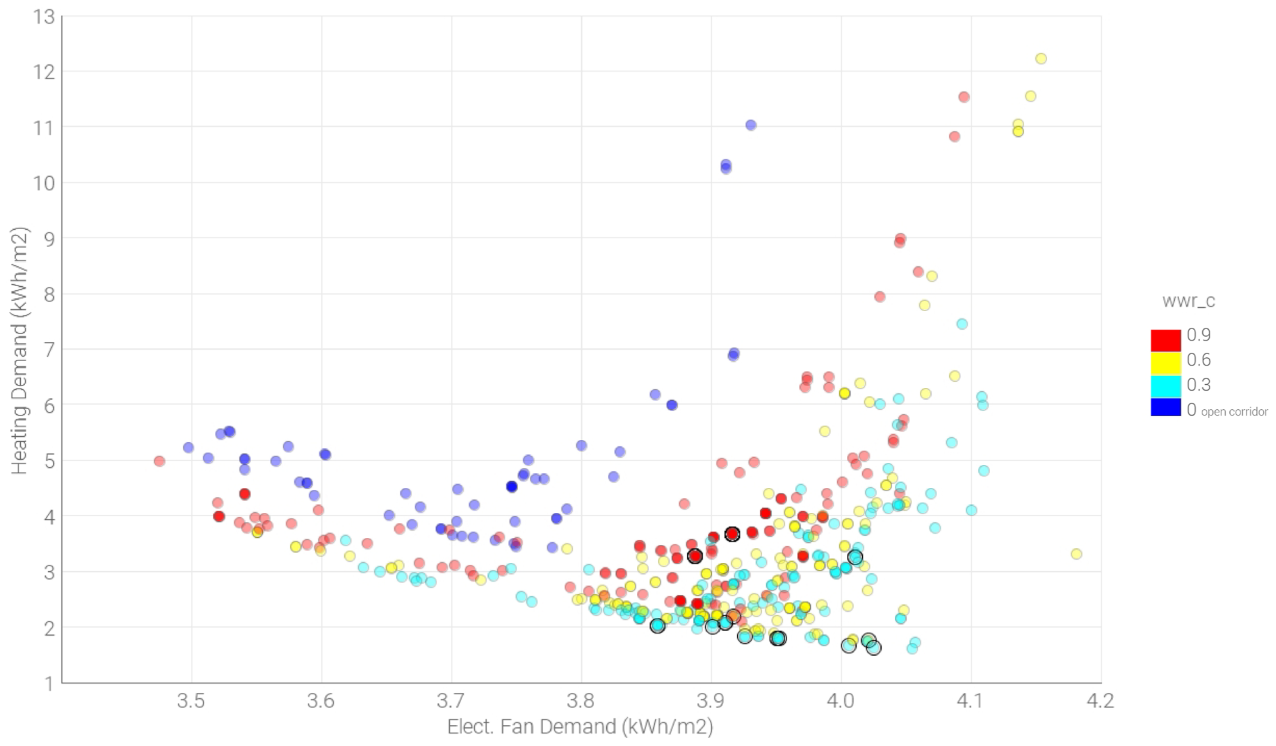


Figure 4.1.7: wwr_c values distribution with regards to Elect. Fan Demand and Heating demand values.

wwr_i

The window-to-wall ratio of the interior wall (wwr_i) appears to play a determining role in the overall thermal comfort performance. As it can be clearly seen in Figure 4.8, the design space distribution is very much dependant on the wwr_i values. More specifically, low wwr_i values lead to low thermal comfort ones, while for the rest of the values no clear conclusion can be drawn.

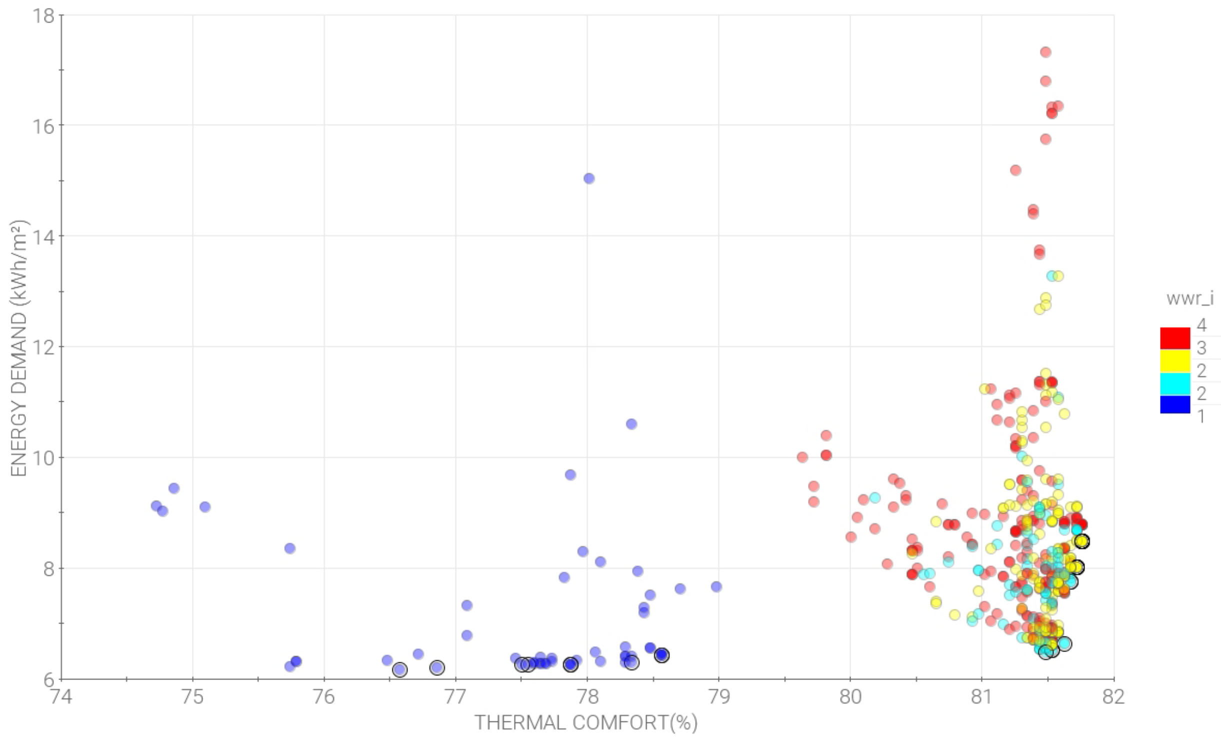


Figure 4.1.8: wwr_i values distribution with regards to Thermal Comfort and Energy Demand values

4.1.2 Window properties: SHGC & VT

SHGC

Regarding the SHGC it is clear from Figure 4.1.10 that the most preferable values are those of 0.4, 0.5 and 0.6. Higher values seem to lead to increased energy demand. Looking at Figure 4.1.9, we can specifically determine that the increased energy demand is due to the electric fan demand for ventilation, as the two variables have a high positive correlation of 0,795. On the contrary, as indicated in Figure 4.1.10, the lowest values, increase the percentage of the 'Too cold' hours and thus are not preferred either.

VT

VT values appear to have a small impact towards the outputs and no conclusion can be drawn even though several graphs were explored seeking for patterns and possible correlations.

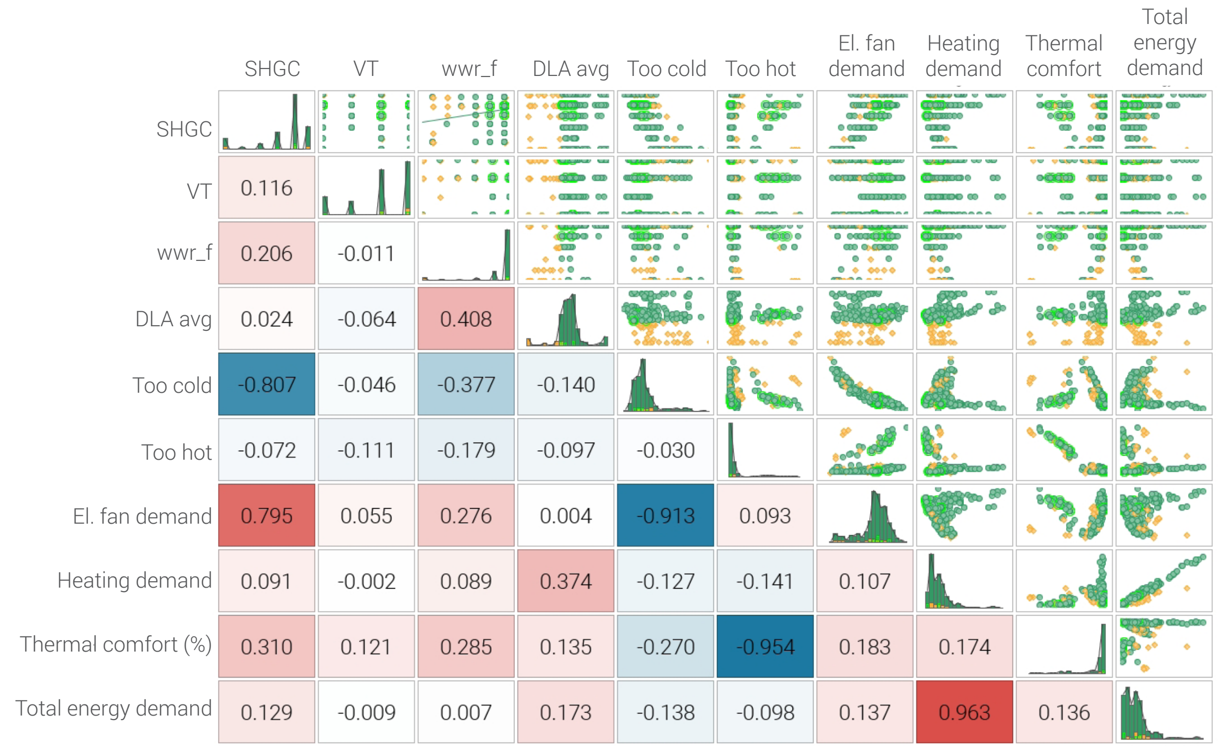


Figure 4.1.9: Scatter Matrix chart indicating Pearson Correlation between SHGC, VT, wwr_f and relevant outputs.

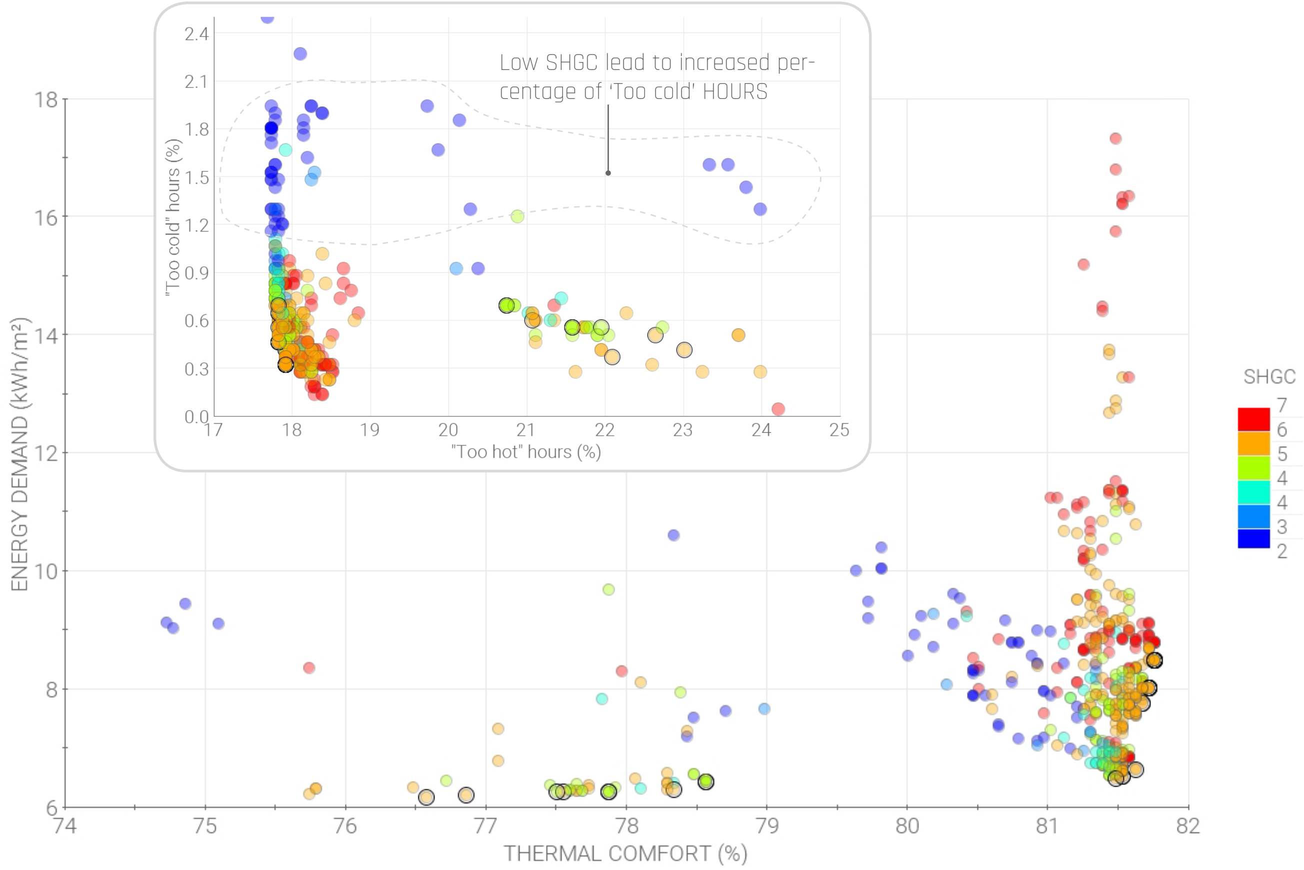


Figure 4.1.10: SHGC values distribution with regards to Thermal Comfort and Energy Demand values.

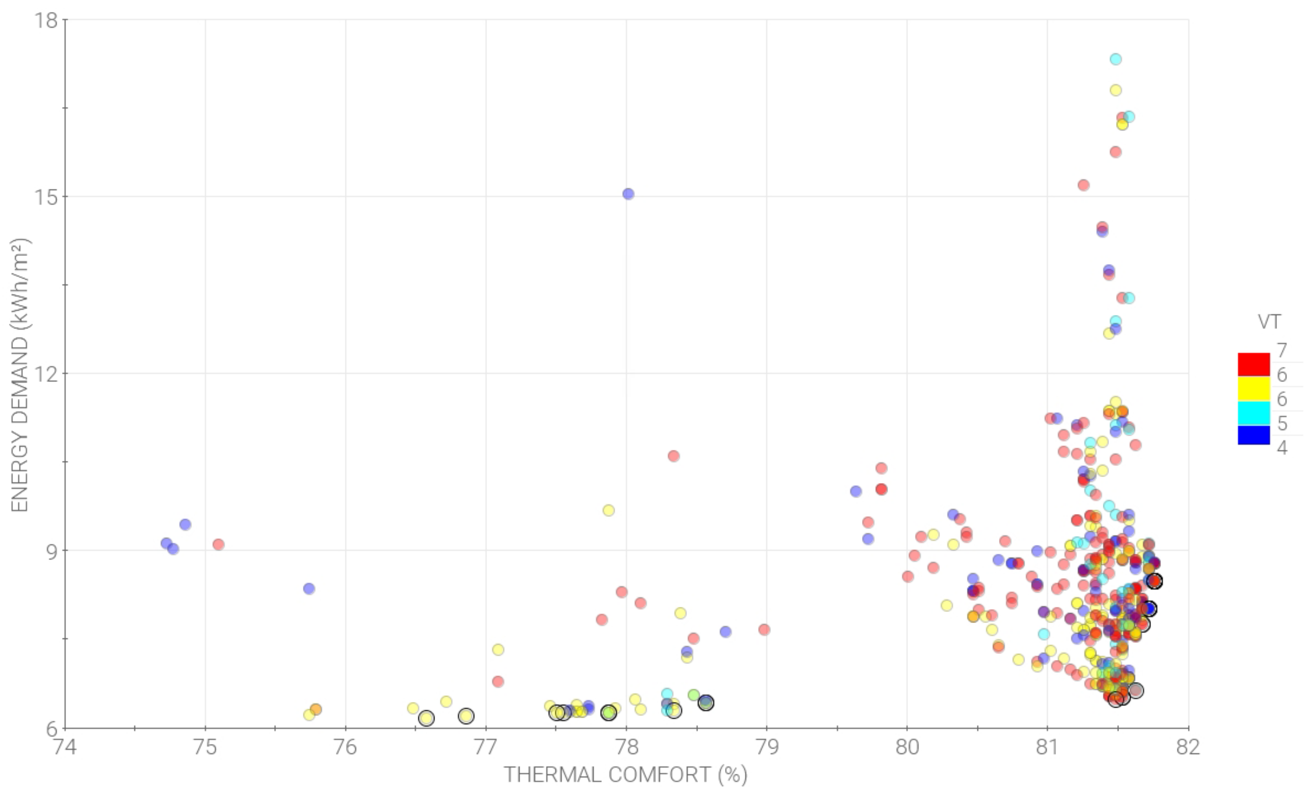
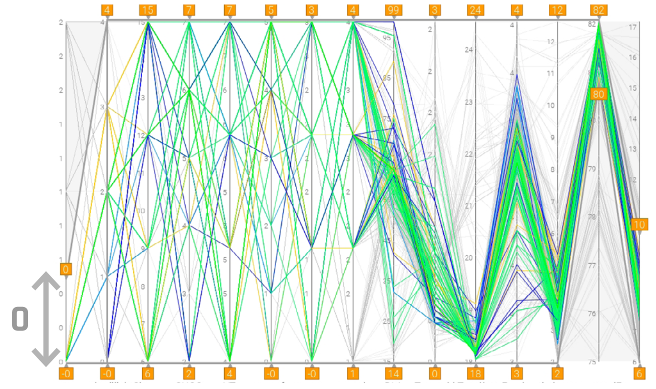


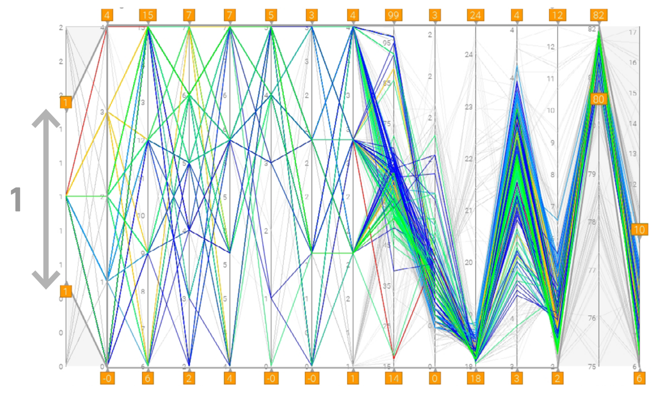
Figure 4.1.11: VT values distribution with regards to Thermal Comfort and Energy Demand values.

4.1.3 Orientation & shading type

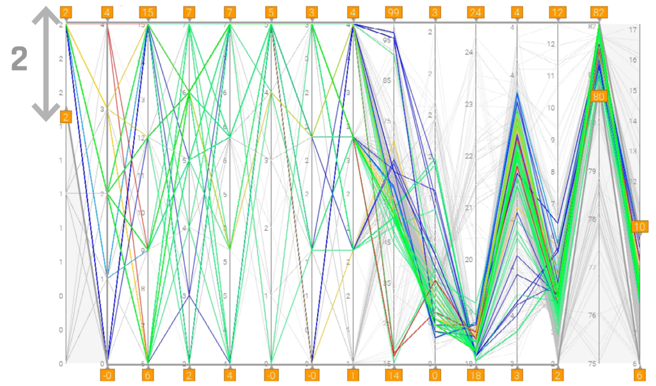
As already mentioned in paragraph 4.1.2, the most preferable shading type with regards to the objectives, is the horizontal louvres. In order to investigate whether or not the shading type is affected by the different orientations, we make use of the Parallel Coordinates chart. Using this tool, we are able to filter the designs by assigning minimum and maximum values to the given variables. Figure 4.1.12 shows the shading types that give Thermal Comfort values above 80% and



South orientation (orientation=0), includes the highest number of results. The most preferred shading type is the horizontal louvres.



For south-east orientation (orientation=1), the selected shading types include both horizontal louvres and light shelves.



South-west orientation (orientation=2), presents the worst range of energy demand values. The dominant shading type is once again the horizontal louvres.

Shading type
- Vegetation
- Ver. Louvres
- Hor. Louvres
- Int/ext. Light shelf
- Ext. Light shelf

Figure 4.1.12: Parallel Coordinates graphs for the three different orientations, indicating shading types that lead to Thermal Comfort values above 80% and Energy Demand values below 10 kWh/m².

4.1.4 Best performing designs (Pareto Front)

All the designs solutions that are part of the Pareto Front are presented in Table 4.1.1. The designers have then the freedom to choose any of the solutions. In order to further understand what are the preferable values of variables in the resulted designs, we identify the ones that have the best performance in each of the objectives, as well as designs that adequately fulfil both the objectives. Since we only have two objective, such a selection is possible through the scatter plot chart (Figure 4.1.1) by choosing among the Pareto Front designs that are gathered at the bottom right area of the chart.

PARETO FRONT DESIGNS FOR **CLIMATE ZONE A**

ID	wwr_f	wwr_c	wwr_i	R Interior wall (Km²/W)	SHGC	VT	Light shelf depth (m)	Orientation	Shading type	DLA avg (%)	Thermal comfort (%)	Energy demand (kWh/m²)
184	0.8	0,9	0,6	0.5	0,6	7	0.6	2	2	51.61	81,76	8,48
204	0.8	0,9	0,6	0.5	0,6	4	1.5	0	2	61.78	81,71	8,03
242	0.8	0,9	0,6	1.0	0,6	7	0.6	2	2	51.61	81,76	8,48
248	0.8	0,9	0,6	0.5	0,6	7	0.9	2	2	51.61	81,76	8,48
251	0.8	0,3	0,4	1.0	0,6	7	1.5	1	0	62.24	81,67	7,76
253	0.8	0,3	0,4	0.5	0,6	7	1.5	1	0	62.24	81,67	7,76
258	0.8	0,3	0,2	1.0	0,5	6	1.5	1	0	63.04	77,87	6,27
286	0.8	0,9	0,6	0.5	0,6	4	1.2	0	2	61.78	81,71	8,03
313	0.8	0,9	0,6	1.0	0,6	7	0.9	2	2	51.61	81,76	8,48
380	0.8	0,3	0,4	0.5	0,6	7	1.5	1	2	54.08	81,53	6,53
394	0.8	0,9	0,6	1.5	0,6	7	0.9	2	2	51.61	81,76	8,48
424	0.8	0,9	0,6	1.0	0,6	4	1.5	0	2	61.78	81,71	8,03
432	0.8	0,6	0,4	1.0	0,6	7	1.5	1	2	55.49	81,62	6,64
446	0.8	0,9	0,6	0.5	0,6	7	1.2	2	2	51.61	81,76	8,48
448	0.8	0,9	0,6	0.5	0,6	4	0.6	0	2	61.78	81,71	8,03
449	0.8	0,6	0,2	1.0	0,6	6	1.5	1	0	63.47	77,55	6,26
470	0.8	0,3	0,4	1.0	0,6	7	1.5	1	2	54.08	81,53	6,53
482	0.8	0,3	0,2	1.0	0,6	6	1.5	1	2	54.78	78,33	6,30
510	0.8	0,9	0,6	1.0	0,6	4	1.2	0	2	61.78	81,71	8,03
511	0.8	0,3	0,2	0.5	0,5	6	1.5	1	0	63.04	77,87	6,27
517	0.8	0,3	0,2	1.0	0,5	6	1.5	1	2	54.78	78,56	6,44
533	0.8	0,3	0,2	1.5	0,5	6	1.5	1	2	54.78	78,56	6,44
540	0.7	0,3	0,2	1.0	0,6	6	1.5	1	0	59.78	76,85	6,20
559	0.7	0,3	0,2	1.0	0,6	6	1.2	1	0	61.37	76,57	6,17
568	0.7	0,3	0,2	1.0	0,5	6	1.2	1	0	61.37	77,50	6,26
573	0.7	0,3	0,4	1.0	0,6	7	1.5	1	2	51.04	81,48	6,48
575	0.8	0,9	0,6	1.0	0,6	7	1.2	2	2	51.61	81,60	8,48
588	0.8	0,9	0,6	1.0	0,6	7	1.5	2	2	51.61	81,76	8,48

Design that adequately satisfies both objectives (selected from the bottom-right area of Figure 4.1.1)

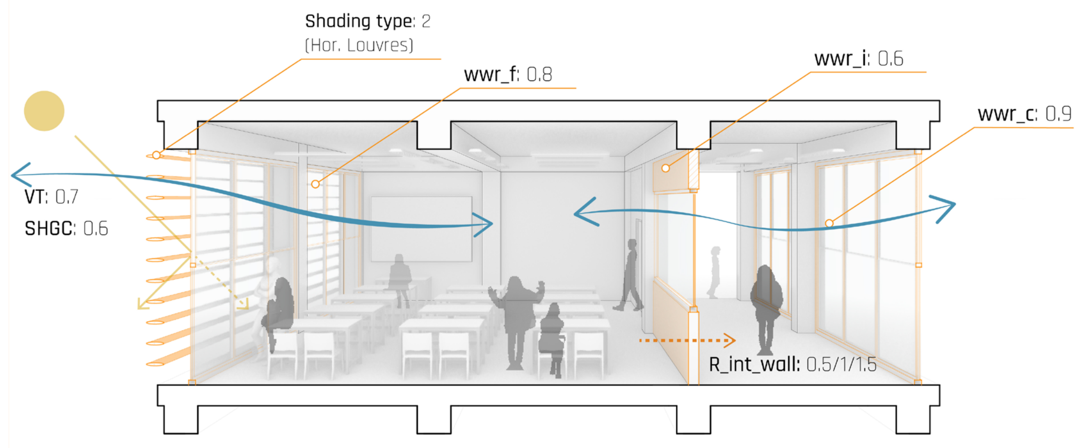
Designs with the highest Thermal Comfort values

Designs with the lowest Energy Demand values

Table 4.2.1: Pareto front design solutions for climate zone A

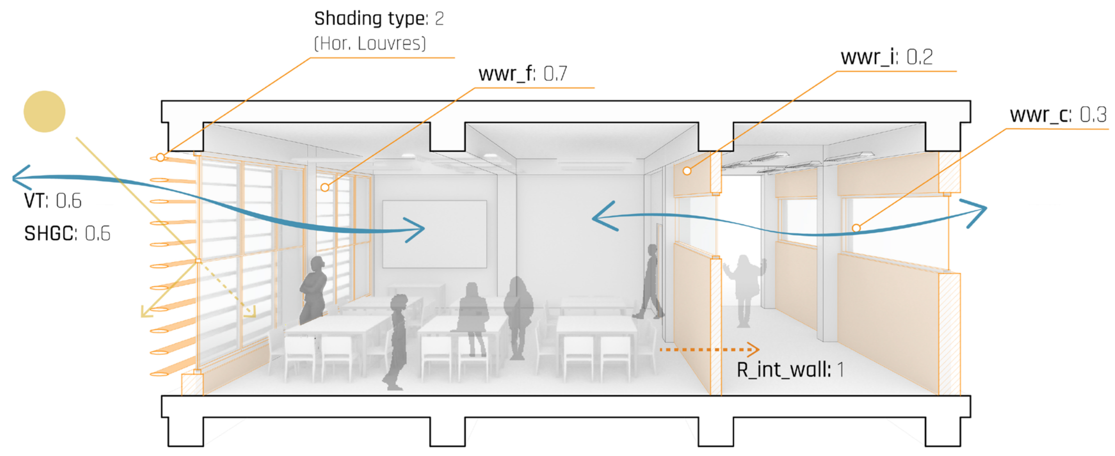
Design with the highest Thermal Comfort

81,76%

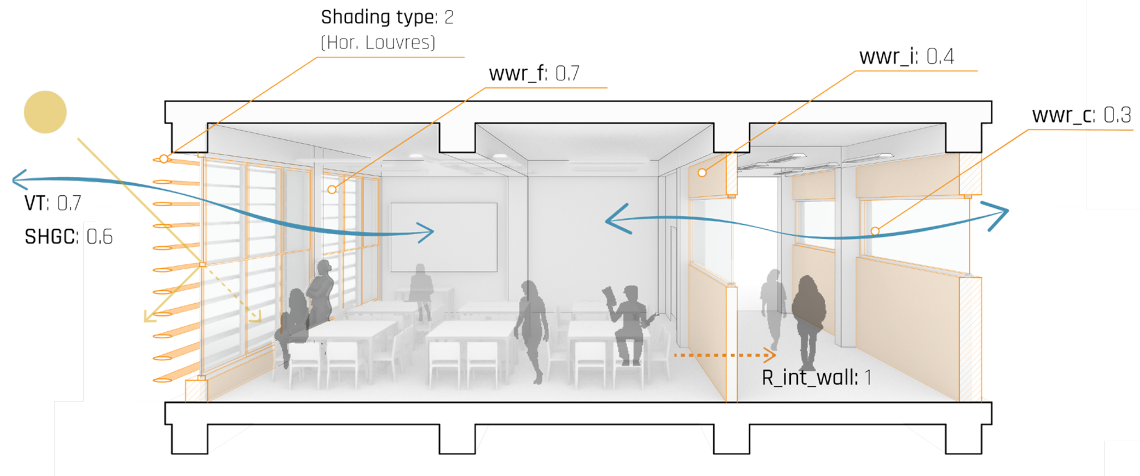


Design with the minimum Energy Demand

6,17 kWh/m²

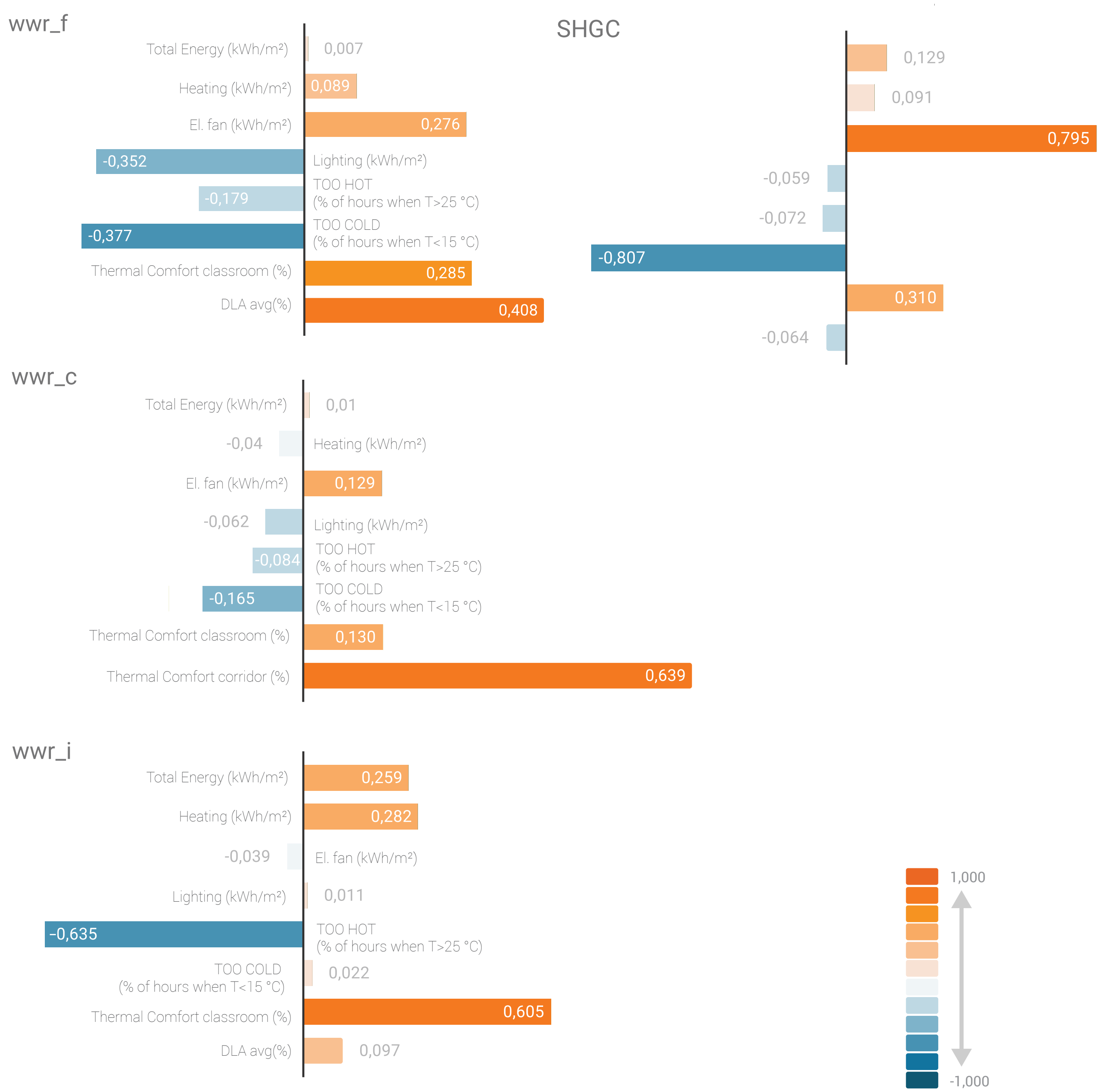


Overall Best designs



4.1.5 Guidelines for climate zone A

As a final phase of the results' analysis for climate zone A, conclusions are drawn in the form of guidelines, summarizing the impact of each variable towards the objectives. This is done using the Pearson Correlation metrics for wwr_f, wwr_c, wwr_i and SHGC which are the most influential variables.

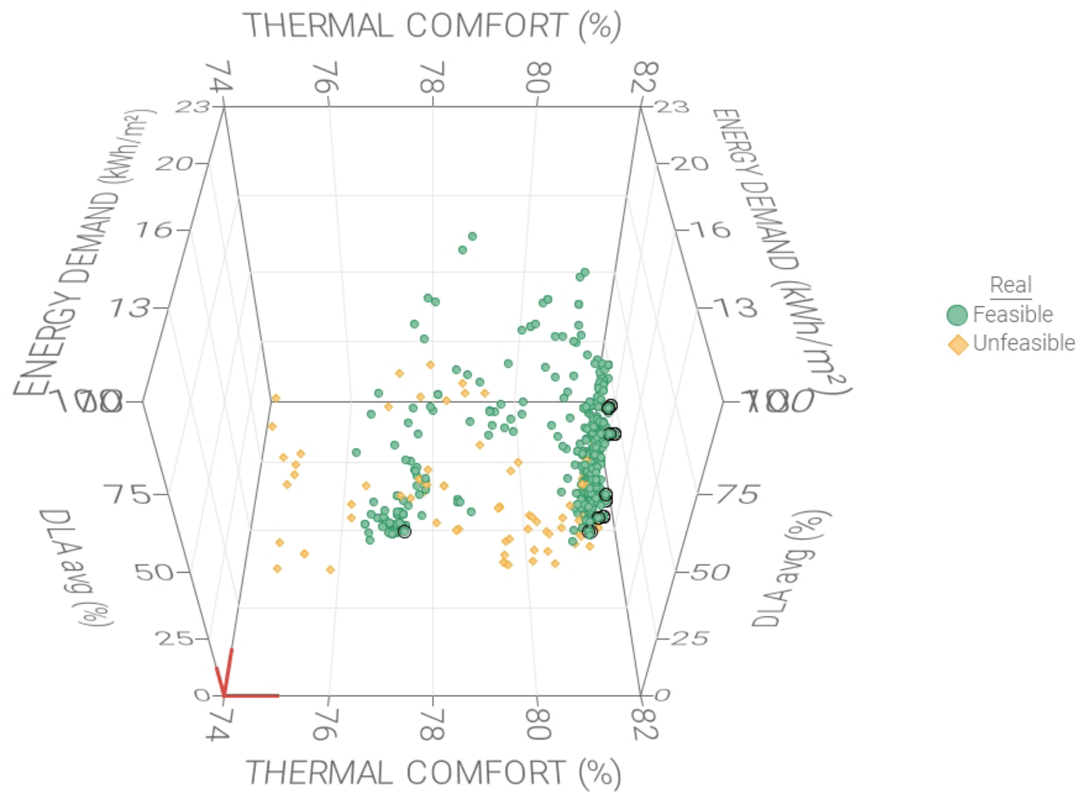


4.2 Results: ZONE B

The optimization took 30 hours to perform the 600 designs, out of which 84 are unfeasible meaning that they did not meet the minimum DLA avg value of 50%, leading to 516 feasible design options. The distribution of the designs with regards to the two objectives can be seen in *Figure 4.2.1.* The range of thermal comfort percentages is between 74-81% while energy demand varies between 10-23 kWh/m².

Figure 4.2.1: Design space solutions represented in a 3D Scatter chart with their respective objective values for Thermal comfort, Energy demand and DLA avg.

414720	600	30	516	21
possible combinations	design iterations	hours duration	feasible solutions	*Pareto Front* designs



Looking at the design space solutions (Figure 4.2.1) it is clear that the algorithm converged towards the highest possible Thermal Comfort values.

	R_Int_Wall	SHGC	VT	lightShelfDepth	orientation	shading	wwr_c	wwr_f	wwr_i
DLA avg	-0.056	0.112	-0.005	-0.184	-0.166	-0.415	-0.156	0.520	0.134
ENERGY DEMAND	0.012	-0.438	0.039	-0.136	-0.076	0.302	-0.324	-0.256	0.263
THERMAL COMFORT	0.036	0.323	-0.129	-0.070	-0.249	0.026	0.223	0.364	0.623

Figure 4.2.2: Pearson Correlation between all the variables, the objectives and the constraint.

In order to get a first idea of the impact that each variable has towards the objectives we plot a Correlation Matrix chart with all the variables (horizontal axis) and the defined objectives and constraint (vertical axis) (Figure 4.2.2). We notice that, as expected, wwr_f has the highest positive correlation to the DLA avg, while shading type has the biggest negative one, though such a notice needs further investigation since shading type belongs to the categorical type of variable. Moreover, SHGC appears to have the highest impact to the energy demand, indicating that higher SHGC values lead to lower energy demand values. Additionally, regarding thermal comfort, wwr_i has the highest positive correlation, followed by the wwr_f. Finally, the R value of the interior wall seems to have a tiny impact and therefore will not be discussed in this chapter.

4.2.1 Window-to-wall ratios

wwr_f

Similarly to the results of climate zone A, the higher wwr_f values appear to give better results with regards to the two defined objectives and mainly to the Thermal Comfort. As indicated in Figure 4.2.4a, the most preferable values (also part of the Pareto Front) are the ones of 0.7 and 0.8.

wwr_c

Regarding the wwr_c values, the most preferable are the ones of 0.3 and 0.6 9 (Figure 4.2.3 & 4.2.4b). The open corridor type leads to high energy demand values.

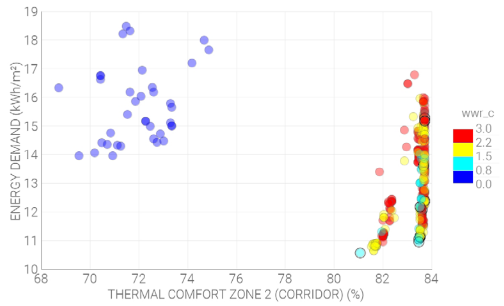


Figure 4.2.3: Distribution of wwr_c values with regards to Thermal Comfort of the corridor and the Energy Demand.

wwr_i

Looking at Figure 4.2.4 we notice again a gap in the distribution of values. The gap correlates to the wwr_i values (Figure 4.2.4c) indicating that the lowest wwr_i values lead to a range of lower thermal comfort values than the rest.

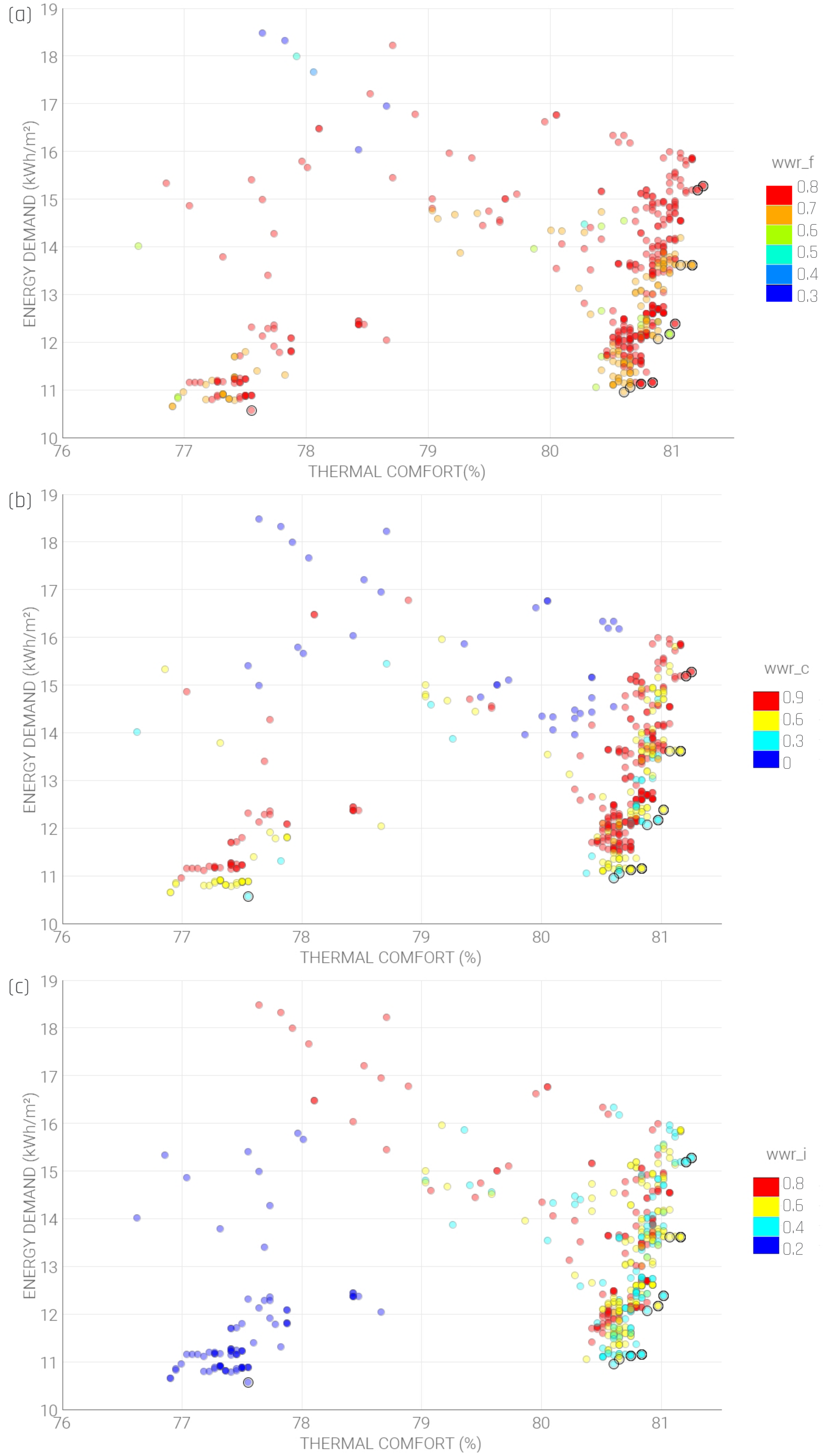


Figure 4.2.4: Design distribution of the wwr_f (a), wwr_c (b) and wwr_i (c) values with regards to the two defined objectives.

4.2.2 Window properties (SHGC & VT)

SHGC

Looking at Figure 4.2.6a, it is clear that the optimization converged towards the highest SHGC values which achieve both the highest thermal comfort values and the lowest energy demand. Aiming to identify more correlations with the rest of the variables we plot a Scatter Matrix chart (Figure 4.2.5). There we notice that SHGC has a big negative correlation with the 'too cold' hours, meaning that higher SHGC values lead to less 'cold hours'. In addition to that we notice that SHGC and wwr_f have a positive correlation, meaning that they both tend to increase their values simultaneously, while we would much rather expect lower SHGC values to compensate for the increased solar gains admitted by the wwr_f.

VT

In comparison to SHGC, no conclusion can be drawn for the VT values as they seem to have a very low impact towards both the objectives (Figure 4.2.6b).

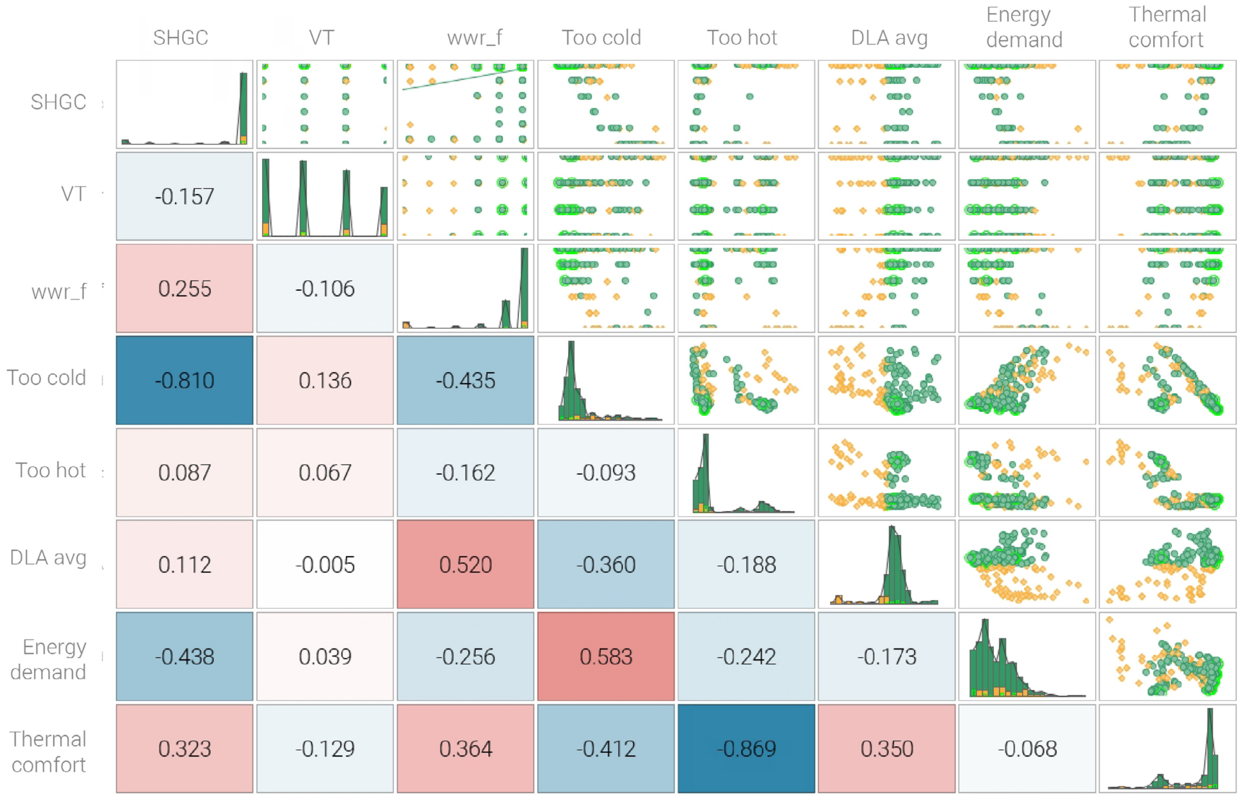


Figure 4.2.5: Scatter Matrix chart indicating correlations between SHGC, VT and wwr_f variables to relevant outputs.

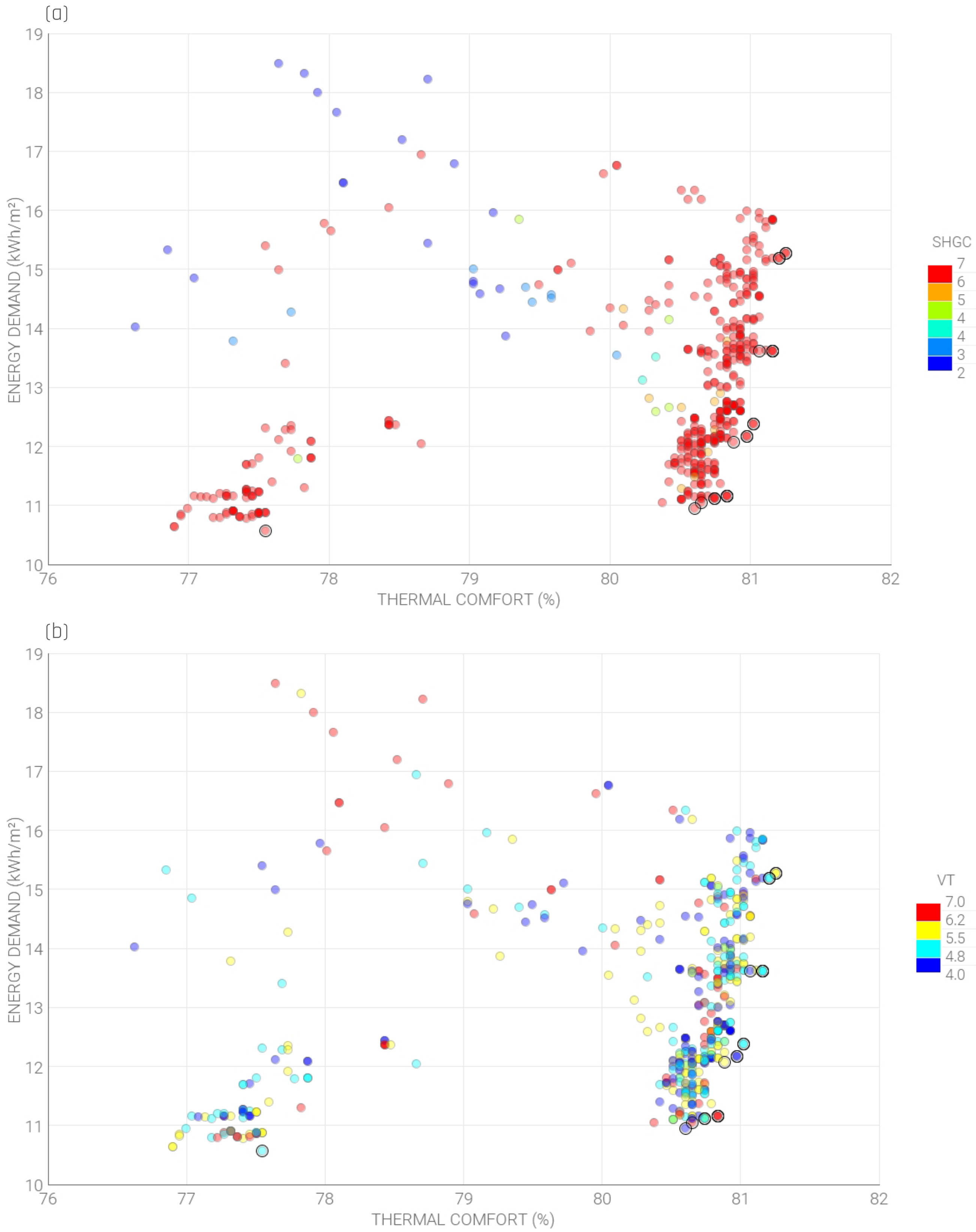


Figure 4.2.6: Distribution of SHGC (a) and VT (b) values with regards to Thermal Comfort and Energy Demand.

4.2.3 Orientation & shading

For the investigation on the impact of the orientation, the Parallel coordination chart is being used. Designs are filtered based on the orientation in an attempt to understand how different orientations affect the objectives, and weather there are correlations between the orientation and other variables i.e. type of shading.

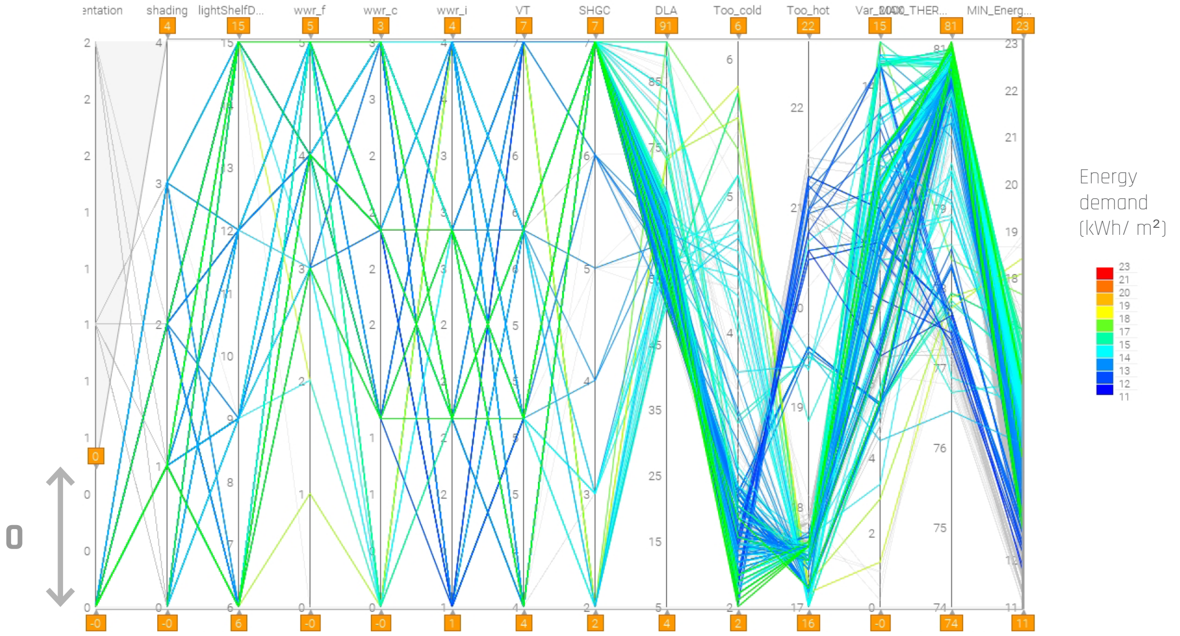


Figure 4.2.7: Parallel Coordinates chart showing the Energy Demand values for orientation=0 (South)

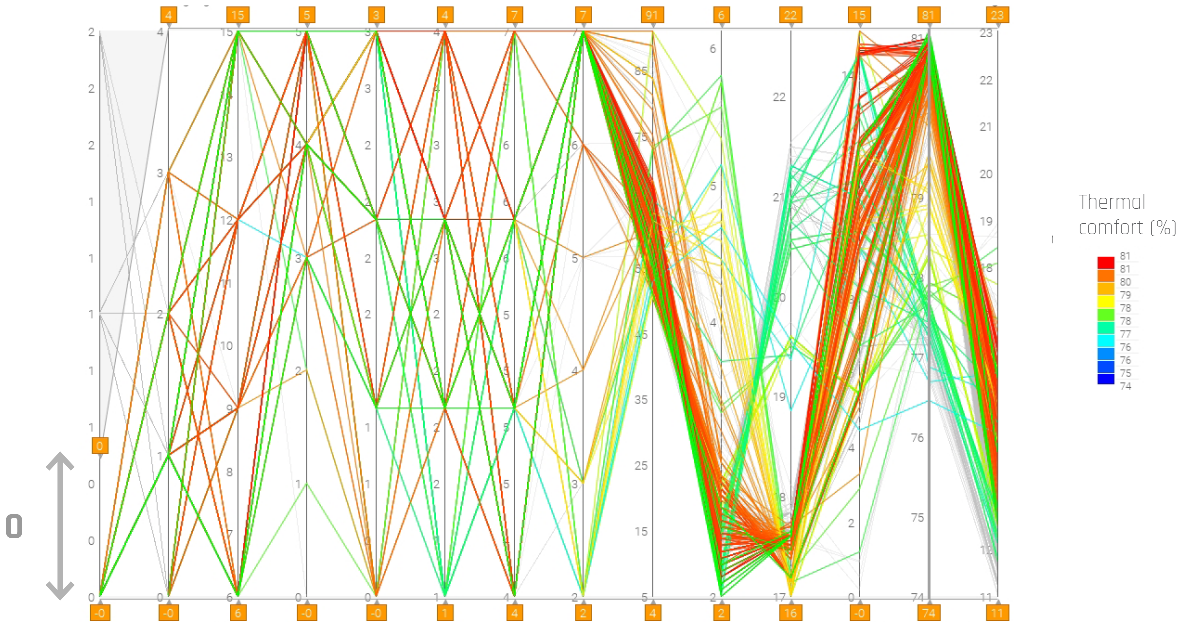


Figure 4.2.8: Parallel Coordinates chart showing the Thermal Comfort values for orientation=0 (South)

Orientation 0: South

Similarly to zone A, south orientation was the most dominant among the design solutions. More specifically, 300 out the 600 designs have south orientation. Looking at Figure 4.2.7, we notice that south orientation results to a wide range of energy demand values (12-18 kW/m²) but still does not include the lowest ones. Regarding the shading type though, no conclusion can be drawn, as there is not indication that certain orientation leads to different shading type selection.

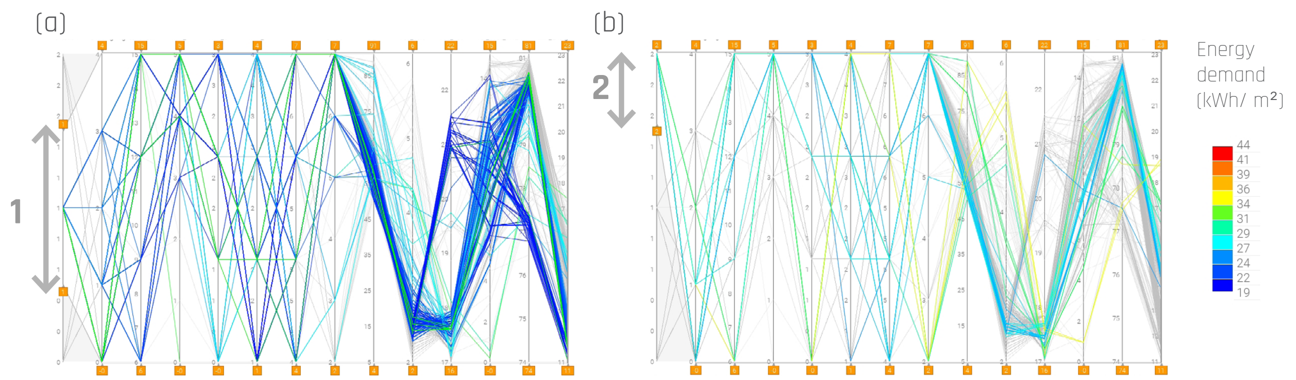


Figure 4.2.9: Parallel Coordinates chart showing the energy demand values for orientation=1 (South-East) (a) and orientation=2 (South-West) (b)

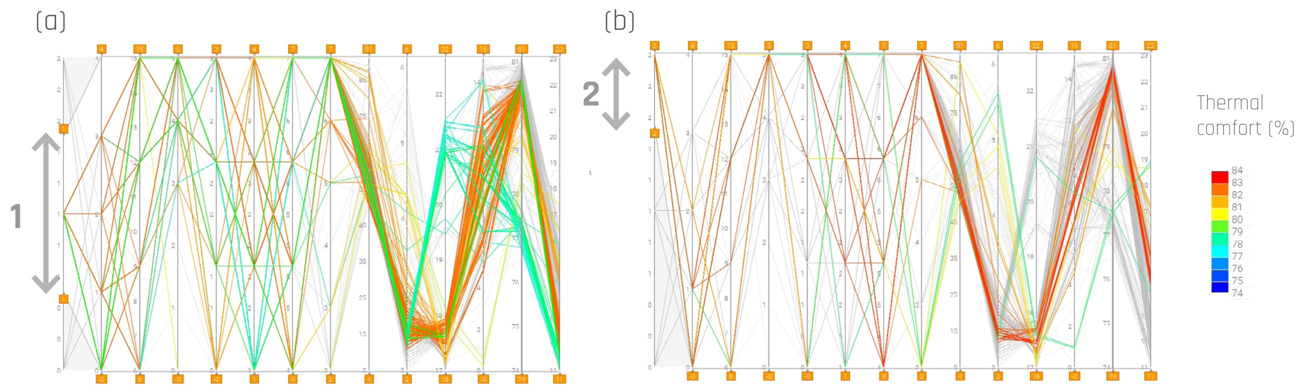


Figure 4.2.10: Parallel Coordinates chart showing the thermal comfort values for orientation=1 (South-East) (a) and orientation=2 (South-West) (b)

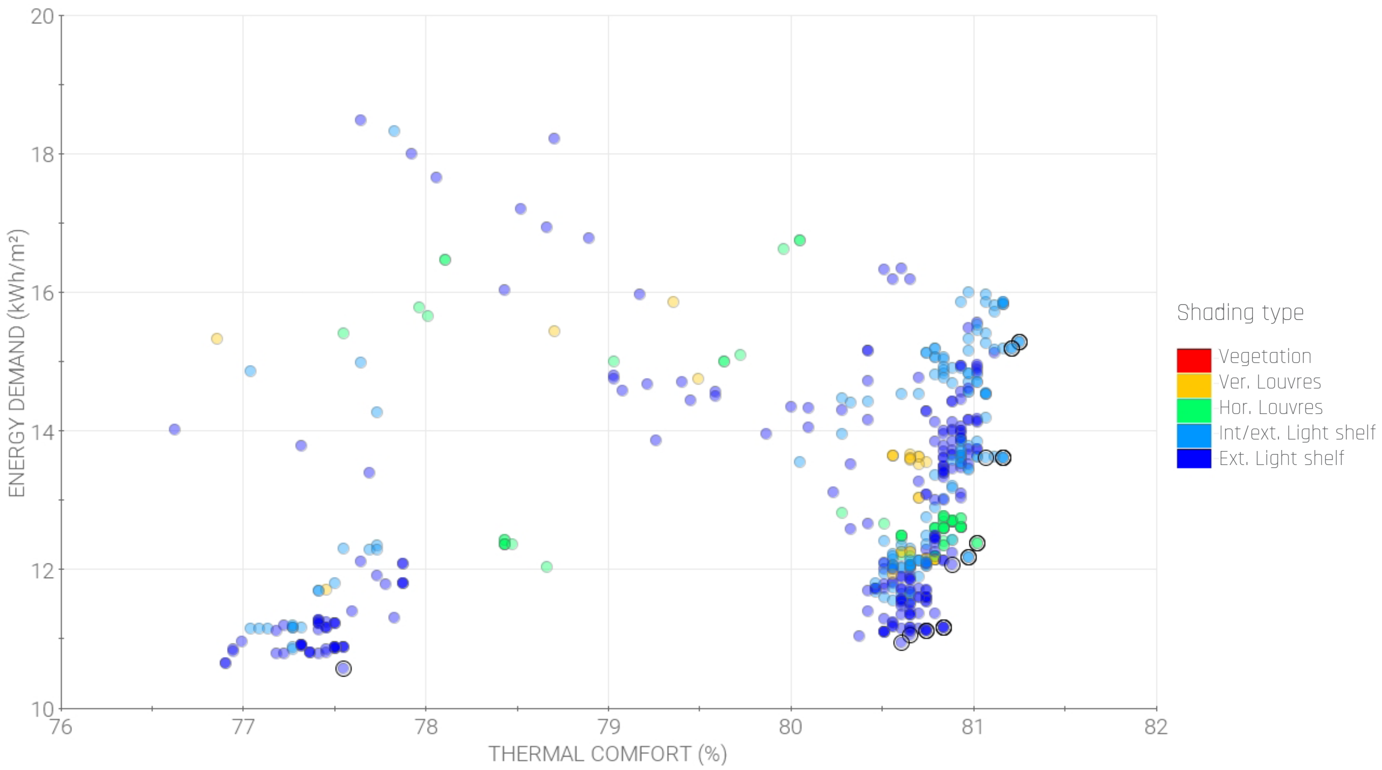


Figure 4.2.11: Design distribution for different shading types with regards to the defined objectives.

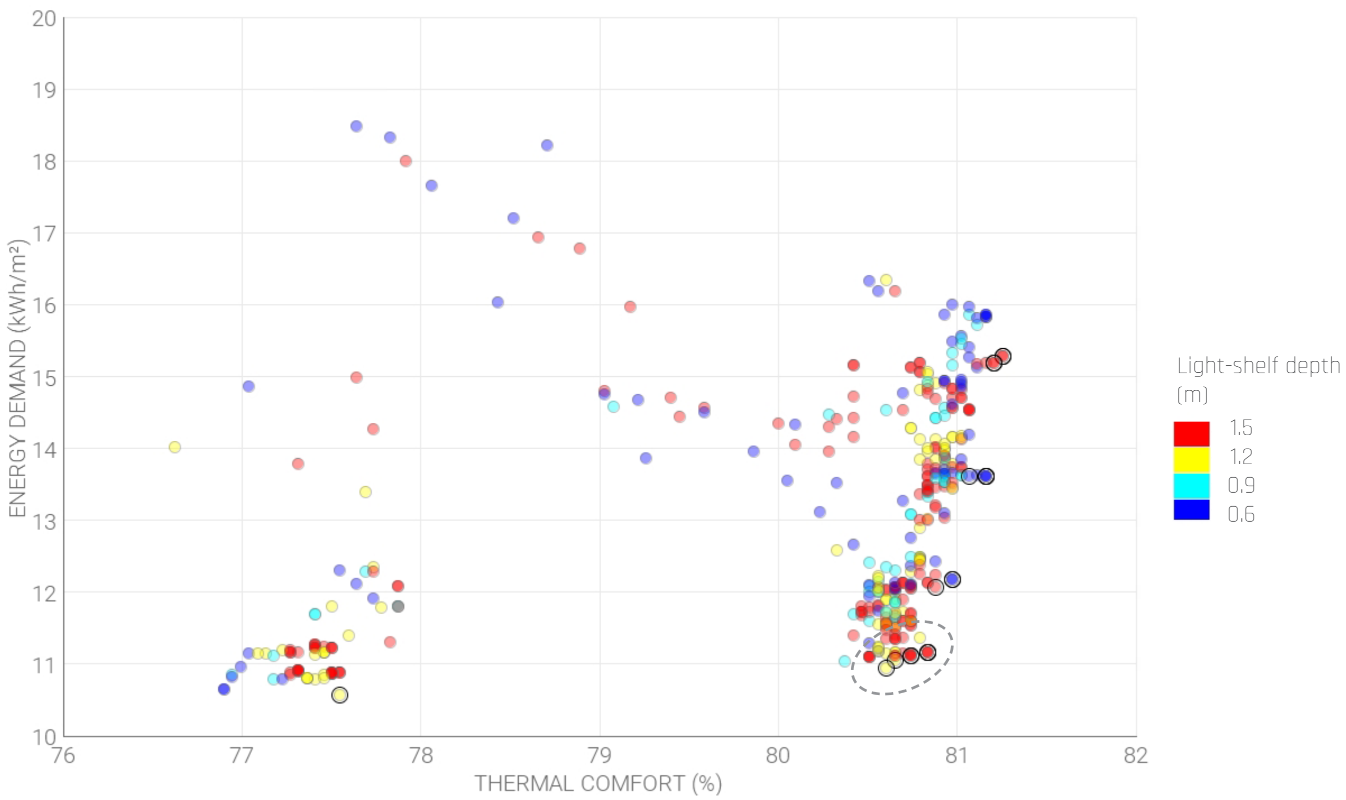


Figure 4.2.13: Design distribution of the solutions that have light shelves as a shading type, for different depth values with regards to the defined objectives.

Shading type

Figure 4.2.11 shows the design distribution of different shading types with regards to the defined objectives. It is obvious that the algorithm converged towards the light shelf shading types which are assigned to 440 out of the 600 solutions.

Light shelf depth

Though various depth values are part of the Pareto Front it can be assumed that the best performing values are the ones with the higher depths (1.2 or 1.5 m) as indicated in Figure 4.2.13.

4.2.4 Pareto Front designs

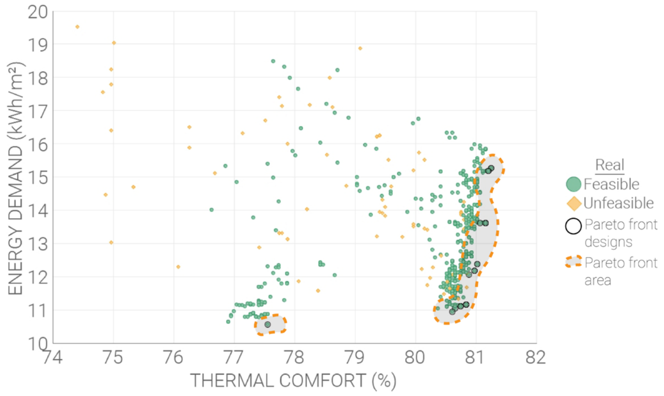


Figure 4.2.14: Pareto front design solutions for climate zone B

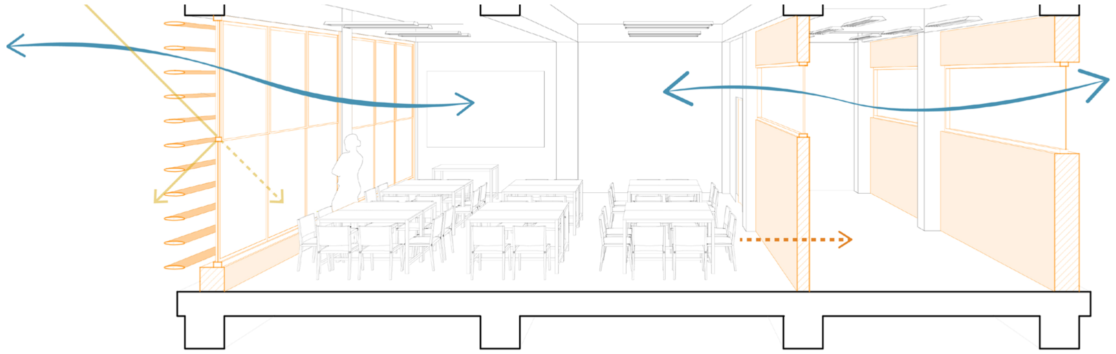
PARETO FRONT DESIGNS FOR **CLIMATE ZONE B**													
ID	wwr_f	wwr_c	wwr_i	R Interior wall (Km²/W)	SHGC	VT	Light shelf depth (m)	Orientation	Shading type	DLA avg (%)	Thermal comfort (%)	Energy demand (kWh/m²)
242	0,7	0,6	0,8	1,5	0,7	0,5	0,6	0	1	62	81,16	13,63
257	0,8	0,9	0,6	1,0	0,7	0,6	1,5	0	1	58	81,25	15,28
339	0,8	0,6	0,6	1,0	0,7	0,5	1,5	0	2	51	81,02	12,39
348	0,6	0,3	0,8	1,5	0,7	0,4	0,6	0	1	55	80,97	12,18
376	0,7	0,3	0,6	1,0	0,7	0,6	1,5	0	0	56	80,88	12,07
430	0,7	0,6	0,8	0,5	0,7	0,5	0,6	0	1	62	81,16	13,63
455	0,8	0,6	0,6	0,5	0,7	0,5	1,5	1	0	57	80,74	11,13
461	0,8	0,9	0,6	1,5	0,7	0,6	1,5	0	1	58	81,25	15,28
469	0,8	0,6	0,6	1,5	0,7	0,7	1,5	1	0	57	80,83	11,17
484	0,7	0,6	0,8	1,0	0,7	0,5	0,6	0	1	62	81,16	13,63
487	0,8	0,9	0,6	3,0	0,7	0,5	1,5	0	1	58	81,20	15,19
499	0,8	0,6	0,6	3,0	0,7	0,5	1,5	0	2	51	81,02	12,39
525	0,8	0,6	0,6	1,0	0,7	0,7	1,5	1	0	57	80,83	11,17
526	0,8	0,6	0,6	0,5	0,7	0,7	1,5	1	0	57	80,83	11,17
532	0,7	0,6	0,8	0,5	0,7	0,4	0,6	0	1	62	81,06	13,62
543	0,7	0,3	0,8	1,0	0,7	0,7	1,2	1	0	53	80,65	11,06
556	0,8	0,9	0,6	0,5	0,7	0,5	1,5	0	1	58	81,20	15,19
564	0,8	0,6	0,6	1,0	0,7	0,5	1,5	1	0	57	80,74	11,13
570	0,7	0,3	0,6	1,0	0,7	0,4	1,2	1	0	54	80,60	10,96
578	0,6	0,3	0,8	1,0	0,7	0,4	0,6	0	1	55	80,97	12,18
599	0,8	0,3	0,4	1,0	0,7	0,5	1,2	1	0	58	77,55	10,58

- Designs that adequately satisfy both objectives (selected from the bottom-right area of Figure 4.2.14)
- Designs with the highest Thermal Comfort values
- Designs with the lowest Energy Demand values

Table 4.2.1: Pareto front design solutions for climate zone B

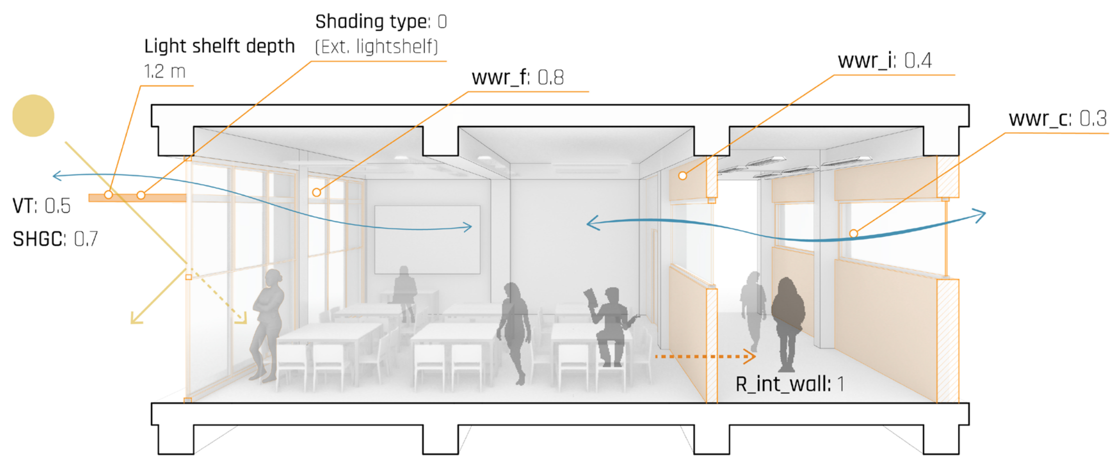
Design with the highest Thermal Comfort

81,25%

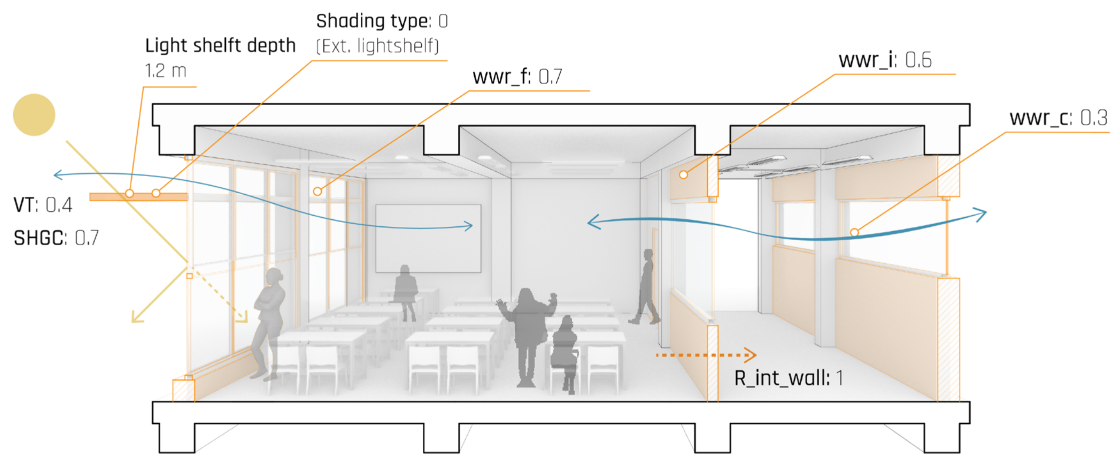


Design with the minimum Energy Demand

10.58 kWh/m²



Overall Best design



4.3 Results: ZONE C

The optimization run for climate zone C lasted 28 hours and led to 600 designs solutions, out of which 58 are unfeasible meaning that they did not meet the minimum DLA avg value of 50%, leading to 542 feasible design options. The distribution of the designs with regards to the two objectives can be seen in *Figure 4.3.1.* The range of thermal comfort percentages is between 75-83.5% while energy demand varies between 19-43 kWh/m².

414720 possible combinations · **600** design iterations · **28** hours duration · **542** feasible solutions · **35** *Pareto Front* designs

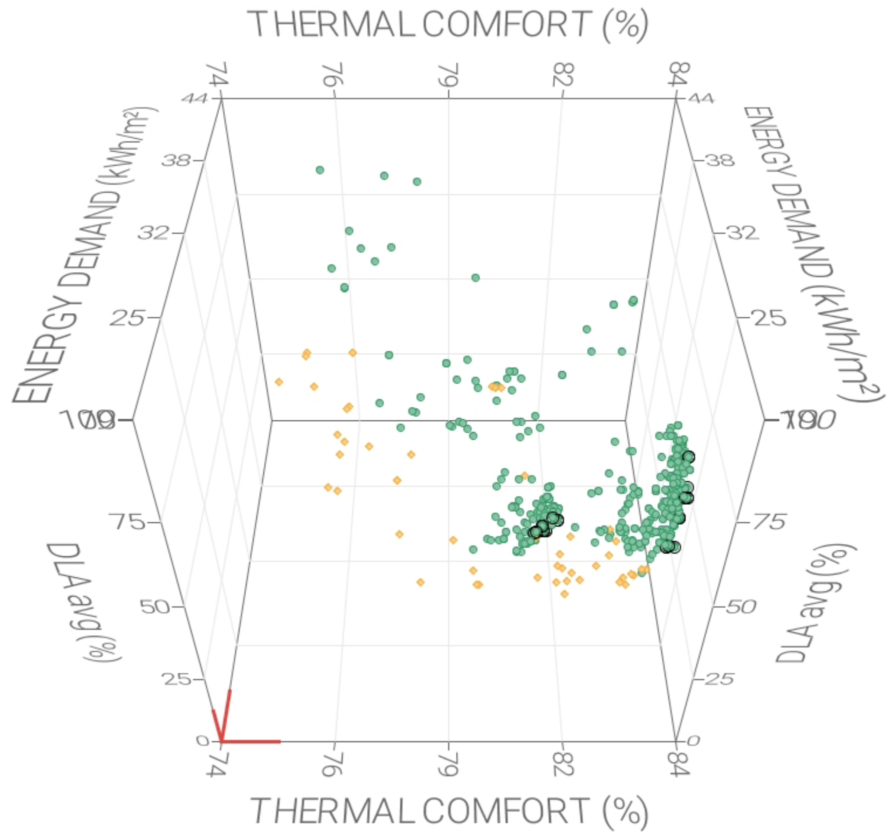


Figure 4.3.1: Design space solutions represented in a 3D Scatter chart with their respective objective values for Thermal comfort, Energy demand and DLA avg.

4.3.1 Window-to-wall ratios

Looking at the Pearson Correlation table for all the different wwr types in relation to the thermal comfort (Figure 4.3.2a) and energy related values (Figure 4.3.2b), we extract the following conclusions. Regarding the thermal comfort, higher values give better results for all the different wwr types. More specifically, higher wwr_f values significantly decrease the amount of percentage of the cold hours and ultimately increase the total thermal comfort of the classroom. Similarly, wwr_c has a positive correlation to classroom's thermal comfort, but further investigation is needed for this correlation as it is not that clear. Finally, higher wwr_i values, similarly to the other two climate zones, significantly increase the thermal comfort of the classroom, as the allow for better cross ventilation, thus decreasing the amount of hot hours. Regarding the energy demand, the Figure 4.3.2b indicates that higher wwr_f values lead to lower energy demand. More specifically, higher wwr_f values lead to lower heating and lighting demand values while increasing the electrical fan demand. The impact of the wwr_c values is in general much lower, but still with a negative correlation to the overall energy demand. Finally, wwr_i values seem to have the least impact.

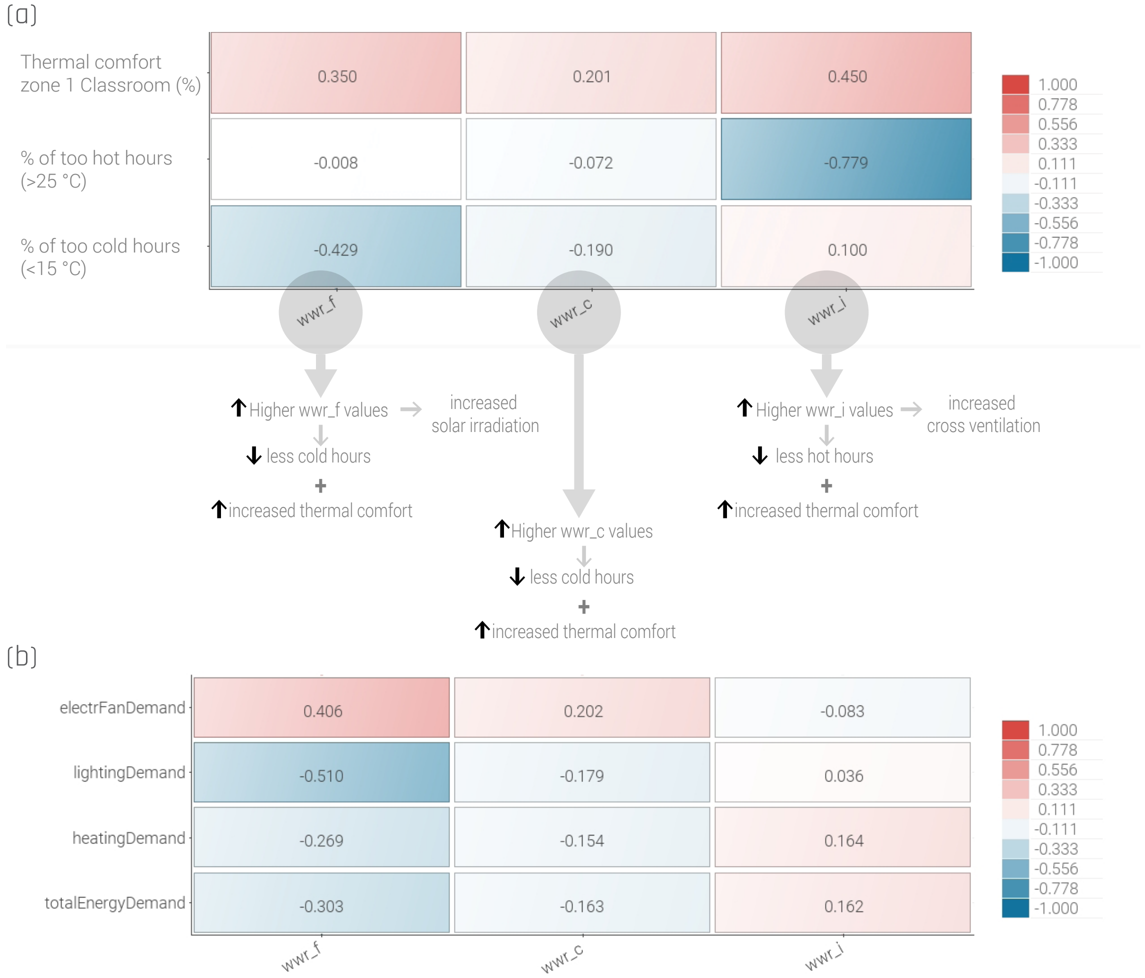


Figure 4.3.2: Pearson correlation between the different window-to-wall ratio variables and the percentages of "Too hot" and "Too cold" hours (a) and different energy demand values (b).

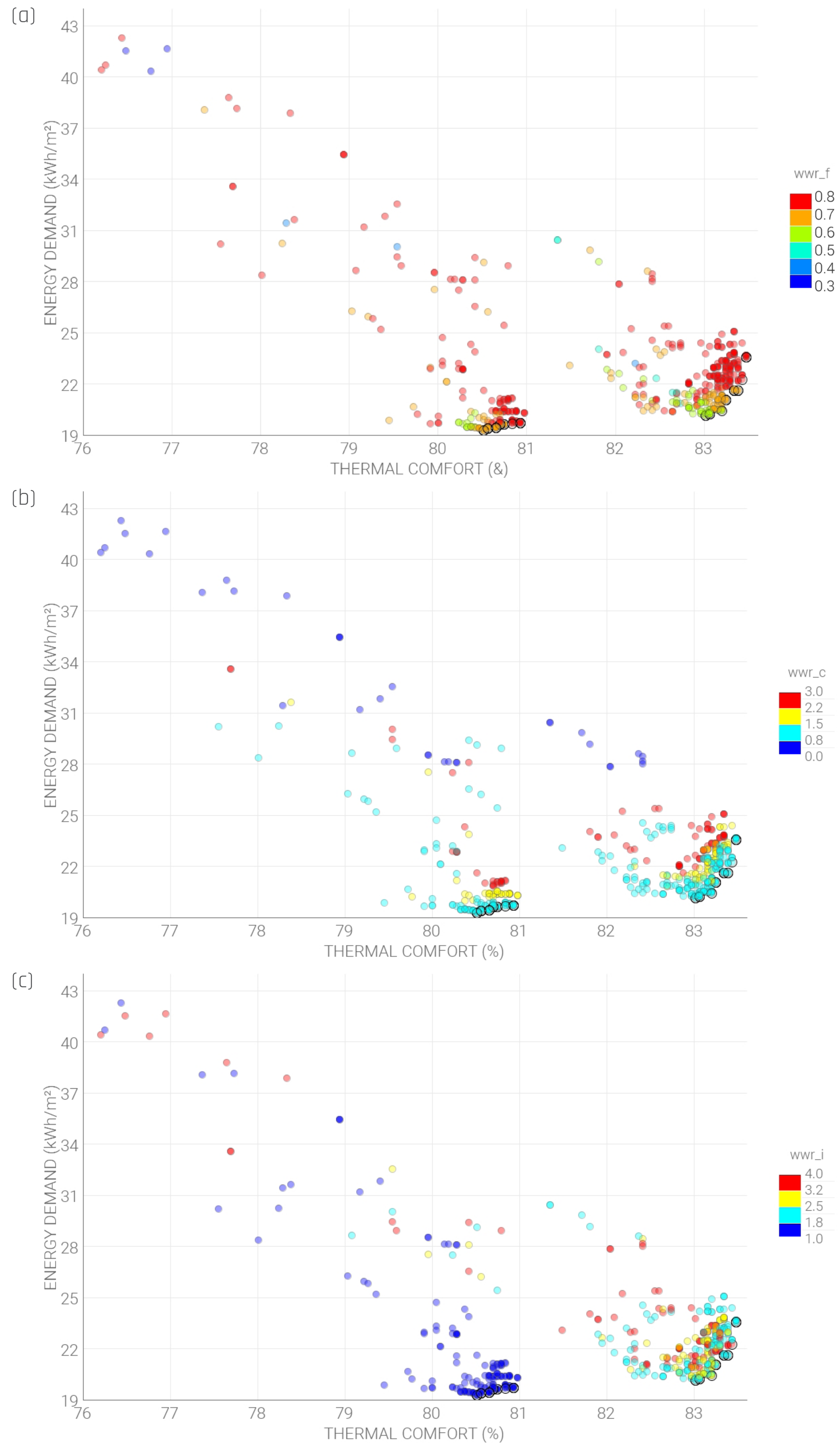


Figure 4.3.3: Distribution of design wwr_f (a), wwr_c (B) and wwr_i (c) values with regards to the defined objectives.

wwr_f
In contrast to the results obtained for climate zones A and B, where the highest wwr_f values were clearly preferred, it seems that the best performing wwr_f values for zone C vary from 0.6 to 0.8 as it is shown in Figure 4.3.3a.

wwr_c
Regarding the optimal wwr_c values, the algorithm clearly converged towards the ones with wwr_c=0.3 as indicated in Figure 4.3.3b. The "open corridor" option (wwr_c=0) is as expected the least preferable for this climate zone, where protection from the north side were corridor is placed is of primary importance in order to minimize the percentage of cold hours. This option gave the highest energy demand values.

wwr_i
The distribution of wwr_i values as shown in Figure 4.3.2c, explains once again the general distribution of the design solutions in the design space, as we can clearly make a distinction between the lower wwr_i values (indicated in dark blue colour on the left side of the chart) and the rest of the values. The gap in between can be attributed to the difference in the thermal comfort values between wwr_I=0.3 and wwr_i=0.6.

4.3.2 Window properties (SHGC & VT)

SHGC
Among the two variables, SHGC is clearly the most impactfull towards the objectives (Figure 4.3.4). More specifically, higher SHGC values, significantly decrease the percentage of cold hours contributing thus to a higher thermal comfort of the classroom. At the same time, higher SHGC values decrease the energy demand, as the heating demand is less as more solar heat is transmitted through the windows, satisfying thus both the objectives

VT
No conclusions can be drawn for the VT values, as they appear to have almost none impact towards the objectives, while looking at Figure 4.3.5b and the distribution of VT values we see that no convergence has taken place.

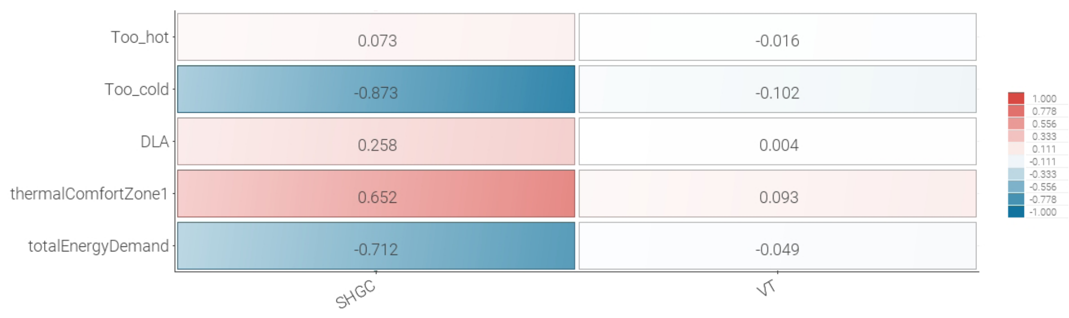


Figure 4.3.4: Pearson correlation between VT, SHGC and the relevant output values.

Figure 4.3.5: Design distribution for SHGC (a) and VT (b) values with regards to the defined objectives.

4.3.3 Orientation & Shading type

Orientation

Similarly to the previous analysis, in order to understand better how orientation correlates to other variables we make use of the Parallel Coordinates chart. Firures 4.3.6-4.3.9 show the ranges of the objective values for each of the different orientations.

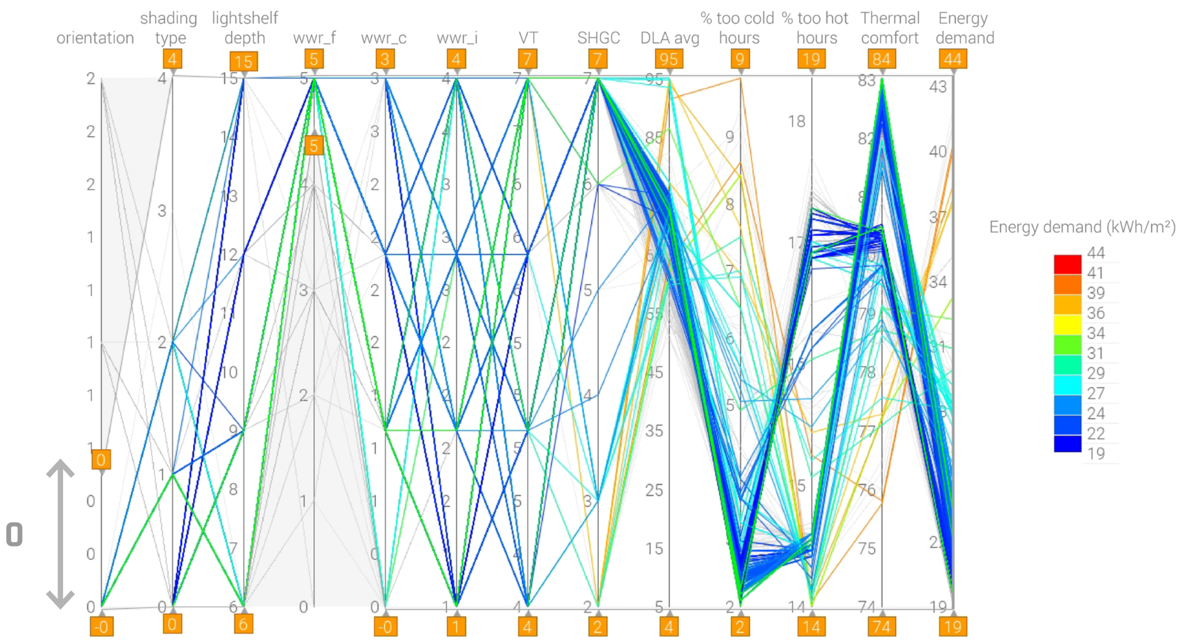


Figure 4.3.6: Parallel Coordinates chart showing the energy demand values for orientation=0 (South)

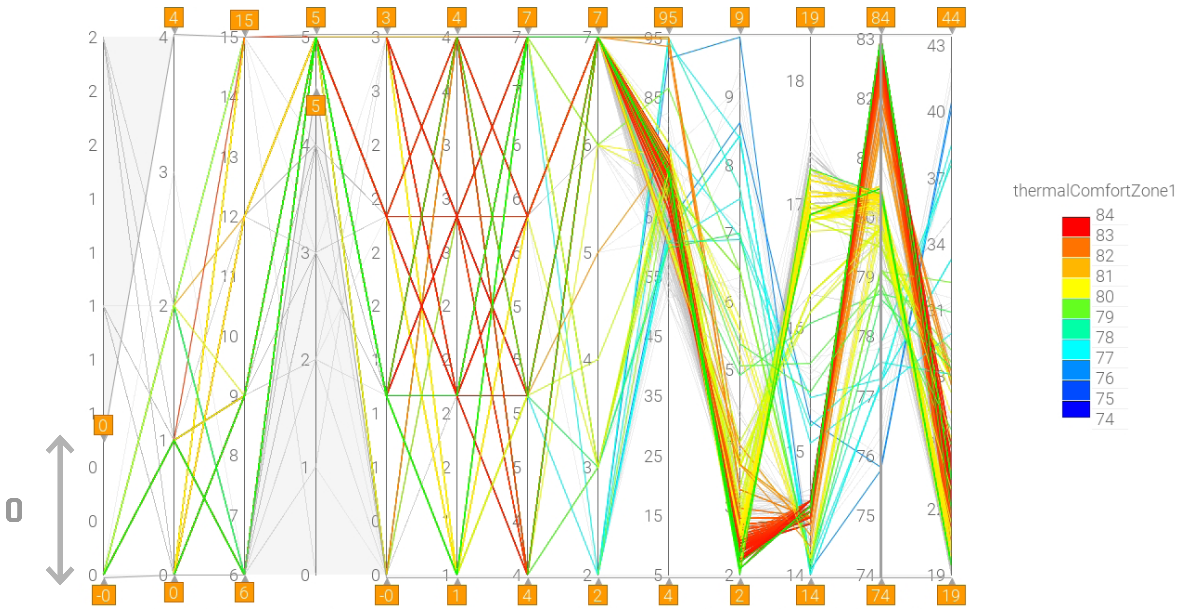


Figure 4.3.7: Parallel Coordinates chart showing the thermal comfort values for orientation=0 (South)

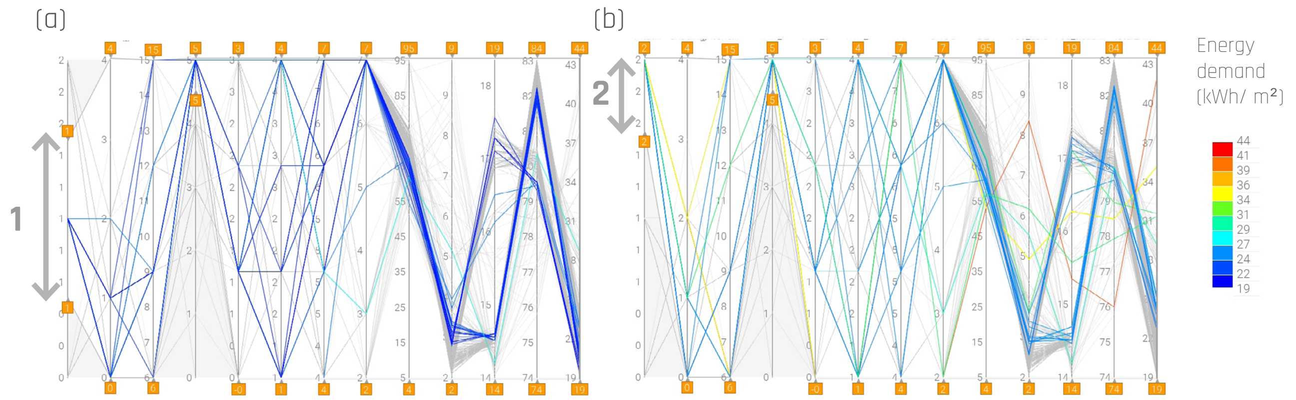


Figure 4.3.8: Parallel Coordinates chart showing the energy demand values for orientation=1 (South-East) (a) and orientation=2 (South-West) (b)

Orientation 0: South

We notice that both lower energy demand values (19-27 kWh/m²) and higher thermal comfort values (81-84 %) are achieved for South orientation (Orientation=0),

Orientation 1: South-east

The design solutions sample is very small when it comes to south-east orientation. Given that sample, and through the Parallel Coordinates chart, we notice that still the lowest range of energy demand values can be achieved. However, the thermal comfort doesn't reach its maximum value of 84% but achieves a high range of 79-83%.

Orientation 1: South-east

The design solutions sample is very small when it comes to south-east orientation. Given that sample, and through the Parallel Coordinates chart, we notice that still the lowest range of energy demand values can be achieved. However, the thermal comfort doesn't reach its maximum value of 84% but achieves a high range of 79-83%.

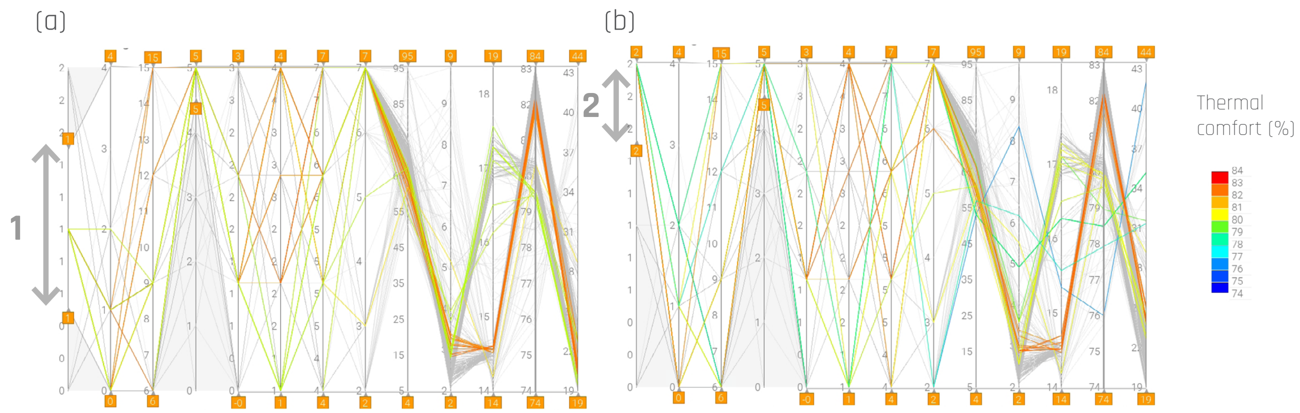


Figure 4.3.9: Parallel Coordinates chart showing the thermal comfort values for orientation=1 (South-East) (a) and orientation=2 (South-West) (b)

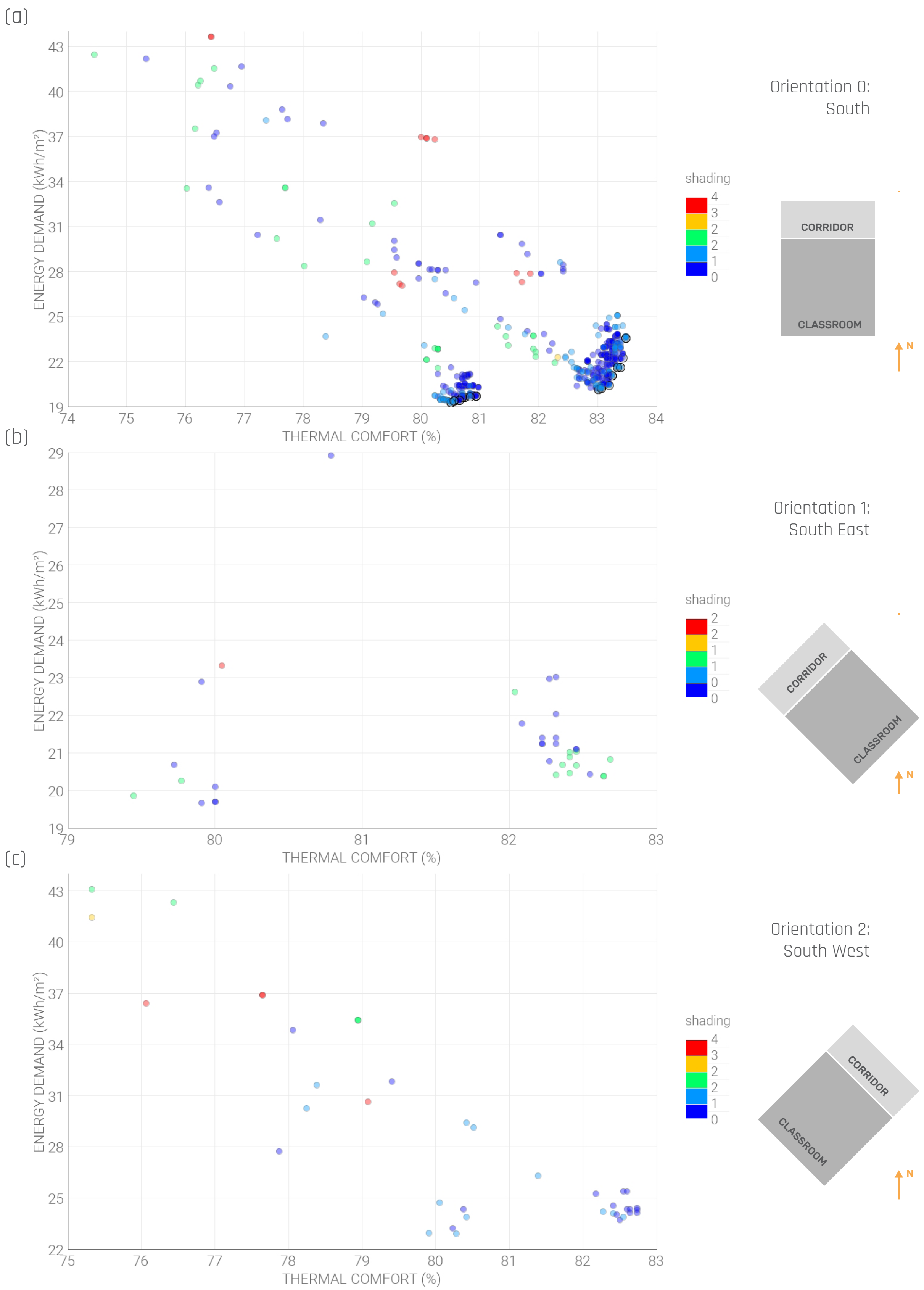


Figure 4.3.10: Distribution of shading type values with regards to the given objectives for different orientations.

Shading type

Regarding the shading type, the optimization converged towards the light-shelf options. More precisely, 545 out of the 600 solutions include light-shelf (either exterior or interior-exterior) as a shading type. Zone C, in comparison to the other ones, needs solar heat the most. Therefore it makes sense that light-shelves are preferred, in comparison to the louvres for example.

Light-shelf depth

In order to understand better weather there are values of the light-shelf depth that are preferable, we make a separate table containing only the design solutions that have light-shelf as a shading type and then we plot a graph indicating light-shelf depth values with regards to the objectives (Figure 4.3.11). The solutions that are mort of the Pareto Front are the ones with the smaller values, namely 0,6m and 0,9m, indicating once again the need for need for solar heat to enter the classroom.

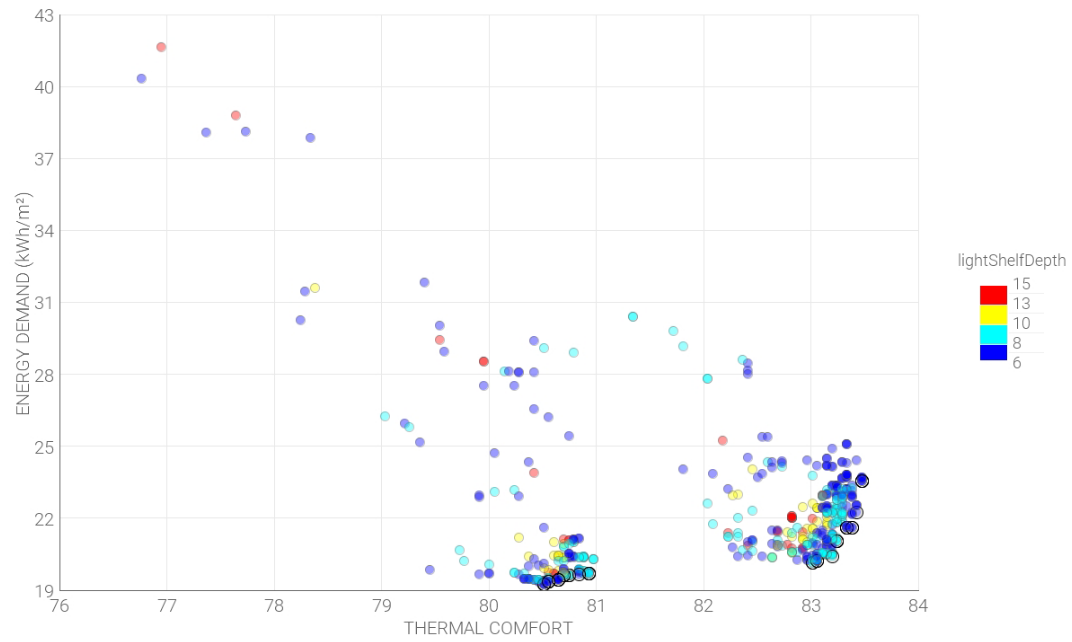


Figure 4.3.11: Design distribution for different light shelf depth values with regards to the two objectives.

R-interior wall

Regarding the R values of the interior wall, no conclusion can be drawn as all the three values were distributed in the design space in such a way that no pattern could be identified, even in combination with other relevant variables such as wwr_i.

4.3.4 Pareto Front designs

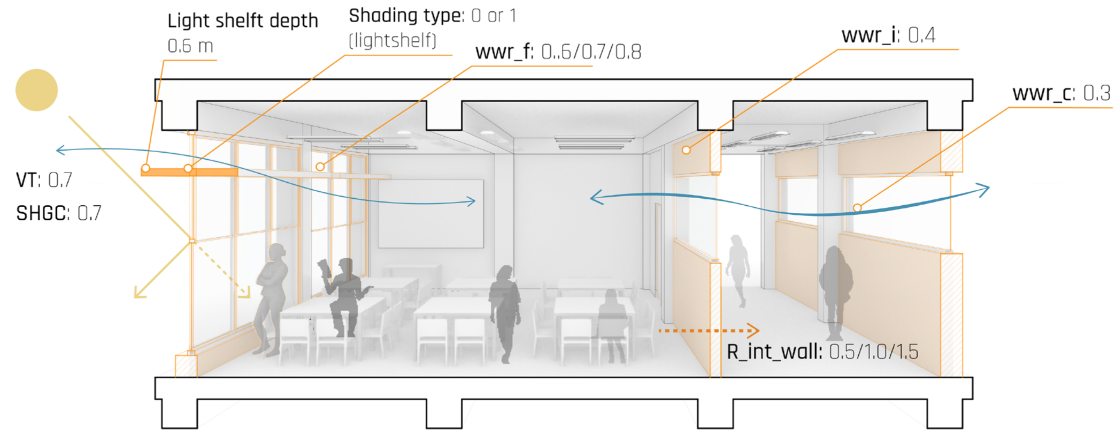
PARETO FRONT DESIGNS FOR **CLIMATE ZONE C**												
ID	wwr_f	wwr_c	wwr_i	R Interior wall (Km²/W)	SHGC	VT	Light shelf depth (m)	Orientation	Shading type	DLA avg (%)	Thermal comfort (%)	Energy demand (kWh/m²)
251	0,7	0,3	0,2	1,5	0,7	0,7	0,6	0	0	72	80,65	19,46
253	0,8	0,3	0,2	1,5	0,7	0,7	0,9	0	0	72	80,93	19,71
261	0,6	0,3	0,4	1,0	0,7	0,7	0,9	0	0	62	83,01	20,17
271	0,8	0,3	0,8	1,0	0,7	0,5	0,6	0	0	69	83,43	22,24
288	0,7	0,3	0,2	1,0	0,7	0,6	0,9	0	0	69	80,69	19,63
306	0,7	0,3	0,4	1,5	0,7	0,5	0,9	0	1	67	83,24	21,05
314	0,7	0,3	0,2	0,5	0,7	0,4	0,9	0	0	69	80,74	19,63
317	0,7	0,3	0,4	1,5	0,7	0,6	0,6	0	1	69	83,33	21,62
319	0,8	0,3	0,4	0,5	0,7	0,7	0,6	0	1	72	83,47	23,57
351	0,7	0,3	0,2	0,5	0,7	0,4	0,6	0	1	70	80,56	19,39
355	0,7	0,3	0,4	0,5	0,7	0,6	0,6	0	1	69	83,33	21,62
370	0,8	0,3	0,4	1,0	0,7	0,7	0,6	0	1	72	83,47	23,57
382	0,8	0,3	0,2	0,5	0,7	0,7	0,9	0	0	72	80,93	19,71
385	0,7	0,3	0,2	1,0	0,7	0,4	0,6	0	1	70	80,56	19,39
389	0,7	0,3	0,2	1,5	0,7	0,6	0,6	0	1	70	80,51	19,28
392	0,7	0,3	0,2	1,5	0,7	0,4	0,9	0	0	69	80,74	19,63
430	0,6	0,3	0,4	1,0	0,7	0,4	0,9	0	1	62	83,06	20,22
431	0,7	0,3	0,2	1,0	0,7	0,6	0,6	0	1	70	80,51	19,28
437	0,6	0,3	0,4	0,5	0,7	0,7	0,9	0	1	62	83,01	20,17
438	0,7	0,3	0,2	1,5	0,7	0,6	0,9	0	0	69	80,69	19,63
460	0,8	0,3	0,4	1,5	0,7	0,7	0,6	0	1	72	83,47	23,57
475	0,6	0,3	0,6	1,0	0,7	0,6	0,9	0	1	61	83,19	20,42
479	0,7	0,3	0,4	1,0	0,7	0,7	0,6	0	1	69	83,38	21,64
480	0,7	0,3	0,2	0,5	0,7	0,6	0,9	0	0	69	80,69	19,63
486	0,8	0,3	0,2	1,0	0,7	0,7	0,9	0	0	72	80,93	19,71
489	0,7	0,3	0,4	1,0	0,7	0,5	0,9	0	1	67	83,24	21,05
498	0,8	0,3	0,4	0,5	0,7	0,4	0,9	0	1	62	83,06	20,22
530	0,7	0,3	0,4	0,5	0,7	0,5	0,9	0	1	67	83,24	21,05
536	0,7	0,3	0,4	1,0	0,7	0,6	0,6	0	1	69	83,33	21,62
549	0,7	0,3	0,2	0,5	0,7	0,6	0,6	0	1	70	80,51	19,28
559	0,7	0,3	0,4	0,5	0,7	0,7	0,6	0	1	69	83,38	21,64
573	0,7	0,3	0,2	1,0	0,7	0,7	0,6	0	0	72	80,65	19,46
591	0,7	0,3	0,2	0,5	0,7	0,7	0,6	0	0	72	80,65	19,46
598	0,7	0,3	0,2	1,5	0,7	0,4	0,6	0	1	70	80,56	19,39
599	0,8	0,3	0,2	0,5	0,7	0,4	0,6	0	1	73	80,83	19,69

Designs that adequately satisfy both objectives (selected from the bottom-right area of Figure 4.3.1)
Designs with the highest Thermal Comfort values
Designs with the lowest Energy Demand values

Table 4.3.1: Pareto front design solutions for climate zone C

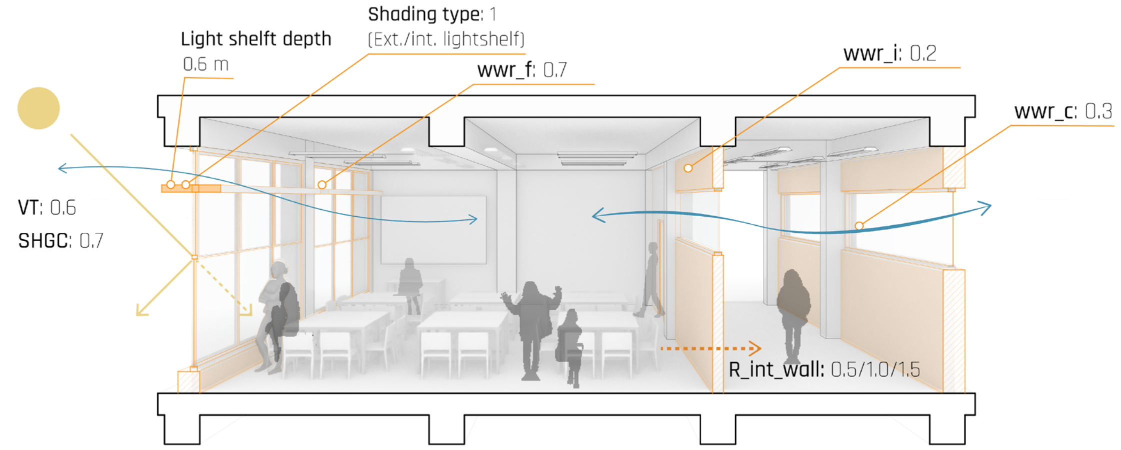
Design with the highest Thermal Comfort

83,47%

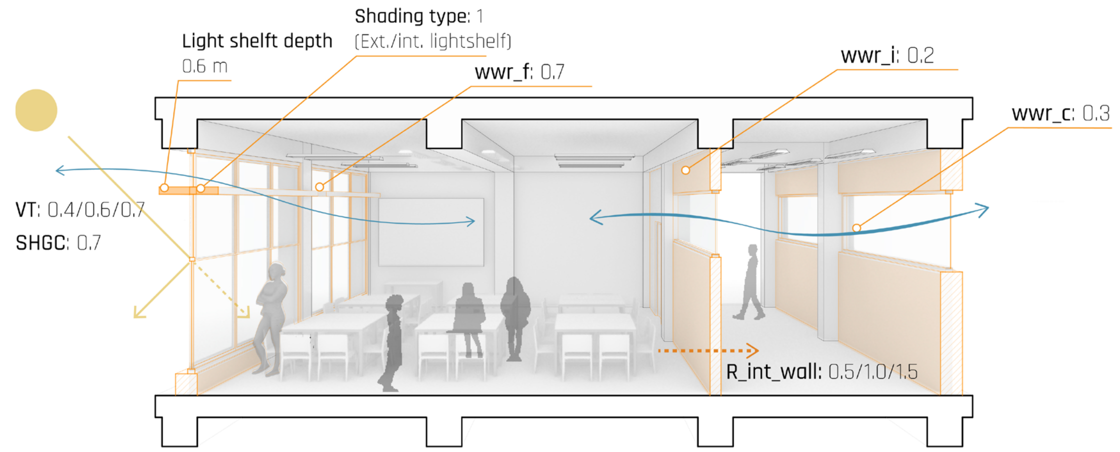


Design with the minimum Energy Demand

19,28 kWh/m²



Overall Best design



CHAPTER 5

DISCUSSION

5.1 Conclusions

5.1.1 General conclusions

This thesis focused mainly on the development of a computational workflow that aims to assist the retrofitting process of the currently under-performing existing school buildings in Greece, by investigating optimal combinations of passive design measurements for the different climate zones of the country. The research included several steps, starting from the relevant literature review in order to obtain the foundation knowledge, and moving on with the development of the Building Energy Simulation and Optimization model. The examined case study included a generic classroom-corridor layout model, which was ultimately optimized using various passive design measures as variables and with respect to the following objectives and constraint:

- Maximizing the Thermal Comfort of the classroom.
- Minimizing total Energy Demand.
- Maintaining sufficient daylight comfort.

The final outcome of the thesis includes both knowledge gained regarding the developed method itself and most importantly knowledge that was formed as an outcome of the optimization results analysis, regarding the impact of the explored passive design measures on the case study model. Regarding the first part, valuable insights were provided regarding the possibilities and future applications of the developed workflow while at the same time highlighting possible risks and limitations. Regarding the second part, conclusions were drawn based on the optimization analysis that was conducted for the two of the three climate zones of Greece, suggesting the passive design interventions with the highest impact with regards to the objectives.

5.2.2 Research questions

How can state-of-the-art Building Energy Simulation and Optimization (BESO) methods, guide the renovation process of existing school buildings in Greece, through passive design interventions, with regards to energy efficiency, daylight and thermal comfort?

Regarding the posed research question, we conclude that BESO methods can contribute to a great extent to the upgrade of the existing school buildings in Greece. The developed workflow proved to be able to provide valuable indications regarding the importance of certain passive design variables among many, ultimately making the whole renovation process more effective and efficient at the early design and decision making stages. Moreover, the simulation and optimization tools brought to light the real complexity of the design problem and gave a better understanding of the various parameters that are involved in it. Overall, and despite limitations that are later described, the applied method was experienced as a promising tool in the hands of the designers of school buildings in Greece.

What are the most determining passive design parameters to the energy demand and thermal comfort for each zone?

Heating demand:
Regarding the heating demand in zone A, the most impactful variable is wwr_i (Pearson correlation: 0.282). Higher wwr_i values increase the cross ventilation and thus the heat losses. On the other hand, regarding zone B, SHGC has the most determining role (-0.482)-lower SHGC lead to increased heading demand- followed by wwr_i (0.333) and wwr_c (-0.324) . The open corridor option (wwr_c=0) increases the heating demand significantly (from 11% to 15%) while low wwr_i values minimize the cross ventilation and thus the heating demand. Heating demand in zone C is also mainly affected by the SHGC (-0.727) but also the wwr_f values (-0.269) and the shading option. Higher wwr_f values lead to lower heating demand while the least sun protective shading options (light shelves of small length) minimize the heating demand as well, indications that highlight the need for accepting solar gains in this zone.

El.fan demand:
El. fan demand helps us understand better the need for cooling, and is mainly used for comparative conclusions rather than for its actual values. For all zones, the most determining factor when it comes to the el. fan demand is the SHGC, with the pearson correlation to be increased from zone A to C. Regarding zone A, shading type and wwr_i play an important role as well. More specifically, inadequate sun protection or low wwr_i values both lead to and increased percentage of 'too hot' hours, thus increasing the demand for el. fan. Besides SHGC, el. fan demand in zones B and C, depends mainly on the wwr_f (0.373 for B and 0.406 for C) and wwr_c (0.391 for B and 0..202). Higher wwr_f and wwr_c values both increase the demand for el. fan ventilation. For zone C, shading type has a great impact as well, as when short light shelves are combined with high wwr_f values, the el. fan demand is increased.

Lighting demand:
For all the zones, the most impactful variable regarding lighting demand as expected the wwr_f and the shading type, with higher values and shorter in length shadings to contribute to lower lighting demand values.

Total energy demand:
The biggest part of the total energy demand is used for heating. Therefore, the most impactful variables for the total energy demand align to those for heating, as they were previously described.

Thermal comfort:
Among all, for zones A and B, the most influential variable to the thermal comfort values is wwr_i More specifically, this can be attributed to the fact that lowest wwr_i values do not allow for adequate cross ventilation, leading an increased percentage of 'too hot' hours (above 25 °C) and ultimately to decreased thermal comfort. For zone C though, even more influential than the wwr_i variable is the SHGC. More specifically higher values contribute to higher percentages of thermal comfort with a positive Pearson Correlation of 0.652.

What are the most optimal design solutions for each climate zone?

Zone A
In general, the most optimal designs in zone A are the ones that combine high wwr_f values with horizontal louvres shadings. Preferred SHGC values are the ones of 0.6 while wwr_i values of 0.4 are combined with wwr_c values of 0.3, and wwr_i values of 0.6 are combined with wwr_c values

of 0.9. Regarding the R value of the interior wall, no conclusion can be drawn since its impact is too limited.

Zone B

The best design solutions in zone B are once again the ones with the higher wwr_f values, combined with lower VT values (0.4-0.6). Similarly to zone A, 0.7 is the preferred value for SHGC while wwr_c values of the best designs vary from 0.3-0.9, not giving a clear indication. Regarding the wwr_i values, the higher ones are the most optimal. Finally, regarding the shading type, the light shelves are clearly preferred, combined mainly with 1.5 m depth.

Zone C

Best performing designs in zone C, have high wwr_f values (0.7 or 0.8) while lower values are more preferable for the wwr_i (0.2) and wwr_c (0.3). This might be justified due to the need for protection from the colder north side of the corridor but also due to the fact that lower wwr)i and wwr_c lead to decreased amount of ventilation and thus less heat losses. The most preferable shading type is the one that allows the most solar heat to enter the building, namely light shelves with 0.6m depth. Similarly to the other two zones, the most preferable SHGC value is the 0.7 while no clear conclusion can be drawn for VT and R_interior_wall.

To what extent can passive design interventions improve thermal comfort of the existing schools while minimizing their energy demand and retaining adequate daylight comfort?

Regarding the achieved degree of improvement in relation to the existing reference situation, the best obtained design results from the optimization for zone A indicated an improvement of up to 37% regarding thermal comfort and 52% regarding energy demand. Respectively, for zone B, a 62% reduction was achieved regarding the energy demand, while thermal comfort was increased by 47%. Finally, regarding the energy demand for zone C, it was reduced by 44% while thermal comfort was increased by 49%, reaching the highest value among all zones (83.47%). It should be noted however that these improvements include the gains from the prior to the optimization process of upgrading the glazing and the existing materials.

5.2 Limitations

All the steps taken in the process of this thesis, introduced several assumptions and limitations during their implementation.

Simulation limitations

Model

During the setup of the simulation model, a specific classroom-corridor topology was chosen. The consequent analysis offers results for this specific topology and does not address other classroom topologies found in Greek schools. Other constants applied to this initial model was its position in the middle floor of the school building. This naturally affected the heat flows.

Software

The simulation software that carried out the simulation, namely Grasshopper and its plugins Honeybee and Ladybug, only simulate some metrics to a certain extent. The metric of Daylight Autonomy was chosen, which by its nature does not take glaring issues into account. The glare analysis was left out of the simulation all together, since state of the art metrics for it fail to offer robust results when addressing the whole classroom.

Design decisions

Certain decisions and assumptions were made during the setup of the simulation model. Regarding thermal comfort evaluation, the metric used was based only on the indoor temperatures measured in the classroom and corridor. Though the assumption still succeeds in simulating the effect, taking more relevant factors into consideration might slightly alter the results. As far as natural ventilation is concerned, in the scope of this thesis, only one strategy was set up. More specifically, cross ventilation by opening of windows when the indoor temperature exceeds a threshold. This strategy was based on the current methods used in building schools. The natural ventilation was a decisive factor in the output energy demand and thermal comfort, as it is the only way of passive cooling of the building, and it acts as a limiting factor to the results as more strategies would lead to different results.

Optimization limitations

The genetic algorithms used, explore the design space and highlight a set solution that satisfy the required objectives the most. This can of course help identify designs that were non-intuitive for the designer at the start of the retrofit. However, the task of exploring and evaluating the solutions obtained is still needed. The designer must apply the proposed guidelines to his/her study case and adapt the solution to his/her case study.

Software

The optimizations performed throughout this thesis were proven quite time consuming. More specifically, each optimization run for approximately 30 hours, executing 600 design iterations on a Intel Core i7-8750H MSI laptop. This created a time-costly feedback loop when trying to improve the settings and context of every optimizations. For the same reason, 600 design iterations were decided. More iterations could potentially generate other design solutions, that fit the objectives better.

5.3 Further work

5.3.1 Vision

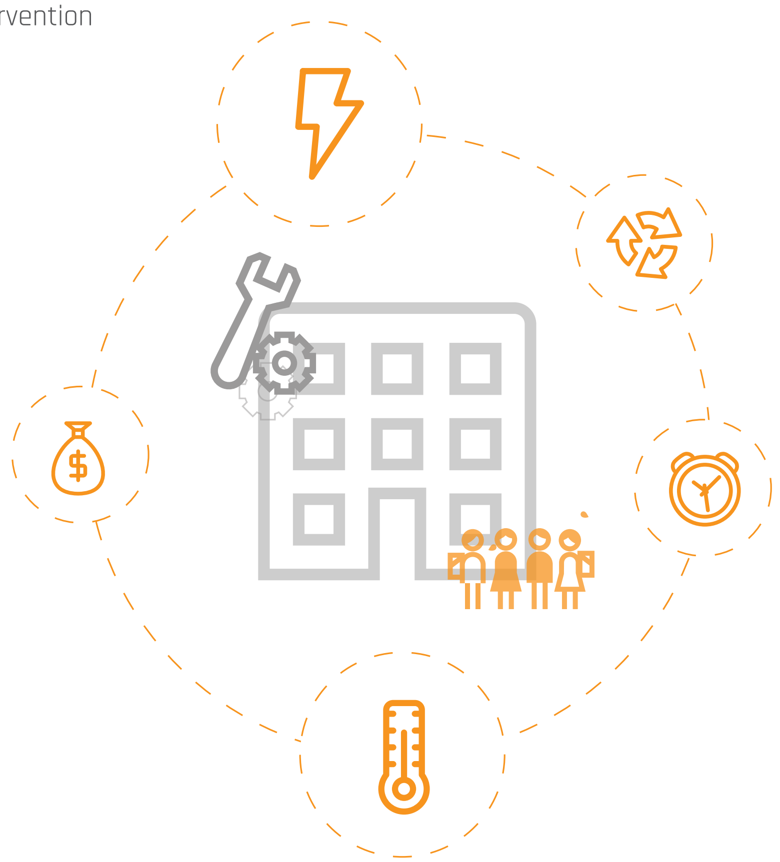
How could such a method evolve to a tool that can be used in practise for the upgrading process of existing school buildings in Greece?

The main source of inspiration of the conducted work was not only the established value optimization processes have offered in the scientific community, but moreover the increasingly promising results such methods have shown when applied to design decision problems. That said, combined with my personal vision of a performance based school building design, helped create a more concrete vision towards using the former to achieve the latter:

"A school building designer, with access to a database of conducted BESO studies and their results, who is able to address his design decision guided by the knowledge and guidelines the collected data can offer him, based on his/her specific case study and its constants."

Moving towards realizing this vision, it was important to analyse the problem in hand. A retrofitting process includes several aspects that need to be taken into account, each introducing complexity to the design task. Some of these are:

- Energy efficiency
- Comfort conditions
- Circularity aspects such as:
- Material selection
- Proximity of resources
- Time frame of the intervention
- Cost



This thesis focused on the variables that affect the optimization of a school design based on two objectives, namely maximizing its energy efficiency and improving the comfort conditions it offers its occupants. The experiments were conducted simulating all 3 major climate zones of Greece. As part of the research conducted important knowledge has been gained not only concerning the parameters affecting these two objectives, but also the useful guidelines that can be extracted from the optimization results themselves. These guidelines can in turn prove extremely valuable during the early design phase of the retrofitting process, as the effect of their application will become clearer.

This thesis ultimately aims to serve the aforementioned vision by:

- Establishing the foundation for consequent BESO studies
- Justifying its importance by highlighting the relevance of its results
- Constitute an example of proposed guidelines, under its specific context
- Explore and define the most appropriate data visualization methods

Therefore, this research can only be seen as a very first step towards the further development of a design tool that could potentially constitute a necessary asset in the hands of the School Building Organization of Greece, during retrofitting processes.

Flow of the design tool

An indicative workflow of the usage of such a tool would involve 2 phases. Initially, the designer would specify the constants concerning his/her design problem. These consist of the static properties of the under-examined classroom-corridor combination such as its orientation, occupancy, ventilation strategy etc. The climate zone of the school would also be specified at this initial stage. Next, the designer would be able to view a list of optimizations conducted with similar inputs to the ones mentioned. Every such study would leverage data visualization methods to project its results in a meaningful manner. Most importantly however, the designer would be able to make use of Parallel Coordinate charts, to explore the values for the proposed guidelines, and come up with the most suitable set of design solutions, namely the ones that satisfy best the constraints and objectives of the problem in hand.

This process can save the designer a lot of time and effort. The increased complexity of satisfying contradicting design objectives is addressed by the optimization processes. This way, the designer can then focus his efforts in integrating the proposed design solution in a real life scenario and address the gap introduced due to the abstractions present in the simulation classroom-corridor model.

5.3.2 Next steps

5.3.2.1 Refinement of the simulation workflow

As a starting point of improvement, the refinement of the simulation workflow is suggested. More specifically:

Daylight
A more detailed daylight analysis is required. At the current stage, daylight is given as a constraint in the optimization phase to ensure adequate daylight comfort. Nevertheless, the fulfilment of the ultimate goal, which is achieving uniform daylight along the classroom while avoiding glaring issues is not guaranteed.

Thermal comfort
An improvement of the thermal comfort assessment that will take into consideration many more factors that are relevant to how occupants experience comfort (such as clothing, metabolic rate, humidity levels etc) is suggested as a next step. In addition to that, factors such as the age of the occupants (students) might play an important role on how they perceive thermal comfort (Parsons, 2014) and are therefore highly recommended to be further investigated and integrated into the simulation model.

Energy demand
Regarding the Energy Demand calculation, at this stage, the demand for cooling is assessed through the el. fan demand, which corresponds to a very small amount within the total energy demand, underestimating this need during the optimization phase. Therefore, a more detailed assessment of the cooling demand is suggested.

Variables enrichment
Furthermore, the addition of more variables is strongly recommended to enlarge the research framework. These could be:

- U-values of the exterior walls which are currently constant.
- Insulating material options
- Material properties such as reflectance and colour. (Assuming a detailed daylight analysis)

Addition of cost, needed time and sustainability factors for each intervention is recommended as well.

Natural ventilation
More ventilation strategies can be explored and applied to the simulation model. These could even act as variables for the optimization so as to determine the most optimal one.

5.3.2.2 Optimization refinement

Regarding the optimization, the first improvement that can be done, is the increase of the number of iterations, as more iterations can ultimately give more optimal results.

Furthermore, refinement of the existing objectives and the addition of more is recommended. One refinement could be the definition of different objectives for each zone based on its specific needs.

6

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APPENDIX

Κατηγορία 2: Κτίρια από το '50 ως το '80

Μειώνεται το πάχος των τοίχων. Κουφώματα σιδερένια. Μόνωση απούσα, στέγες χωρίς μόνωση. Ειδική κατηγορία είναι τα σχολεία της ΜΟΜΑ, προκατασκευασμένα, με μεγάλη θερμική αδράνεια (στοιχεία μπετόν πάχους 50εκ.).

Στις κατηγορίες 1 και 2 υπάρχει συνήθως γραμμική διάταξη όπου στη μία πλευρά είναι ο διάδρομος και στην άλλη οι αίθουσες σε παράταξη. Πολλές φορές οι διάδρομοι είναι υπαίθριοι. Το ωράριο των σχολείων είναι κυρίως πρωινό. Σταδιακά καταργείται τελείως η απογευματινή βάρδια. Έτσι, ενώ απαιτείται θερμική άνεση τις πρωινές μόνο ώρες, είναι σημαντική η διατήρηση της θερμότητας στο κτίριο κατά τη διάρκεια της νύκτας ως τις πρώτες πρωινές ώρες. Αυτό σημαίνει ότι πρέπει να εξασφαλιστεί μεγάλη θερμική αδράνεια στο κτίριο, δηλαδή μεγάλη μάζα στο κέλυφος.

Δυνατές επεμβάσεις στις κατηγορίες 1 και 2:

- Κλείσιμο υπαίθριων διαδρόμων που θα παίξουν είτε ρόλο ανάσχεσης, είτε ρόλο άντλησης θερμικών κερδών
- Μόνωση τοιχοποιίας. Προτεραιότητα στα σχολεία μεταξύ 1950 και 1980 με λεπτούς τοίχους. Στα υπόλοιπα το πάχος των τοίχων καθυστερεί τις απώλειες, οπότε κύρια οδός διαφυγής θερμικών φορτίων είναι η στέγη τους. Η εξωτερική μόνωση της τοιχοποιίας σε αυτά τα σχολεία θα έχει ιδιαίτερα θετικά αποτελέσματα γιατί διαθέτουν μεγάλες αποθήκες θερμότητας, υπάρχει όμως πάντα το ερώτημα του υψηλού κόστους μιας τέτοιας επέμβασης.
- Μόνωση στέγης. Η μείωση θερμικού φορτίου ενδεικτικά παρουσιάζεται ως εξής : Για τη ζώνη Γ: 14%, για τη ζώνη Β: 4,5%, και για τη ζώνη Α: 14%
- Αντικατάσταση κουφωμάτων. Στην περίπτωση αυτή η μείωση του θερμικού φορτίου είναι: Για τη ζώνη Γ: 7%, για τη ζώνη Β: 4% και για τη ζώνη Α: 6%
- Προσθήκη παθητικών ηλιακών συστημάτων. Όπου οι διάδρομοι είναι νότιοι μπορούν να μετατραπούν σε ηλιακούς χώρους σε όλο το μήκος τους, ή κατά διαστήματα σε συνδυασμό με διαπλατύνσεις (χώροι στάσης στο διάλειμμα). Σε αυτή την περίπτωση παρουσιάζεται η παρακάτω εικόνα ως προς τη μείωση θερμικών φορτίων: Για τη ζώνη Γ: 28%, για τη ζώνη Β: 8,4%

Οδηγίες Βιοκλιματικού Σχεδιασμού Σχολικών Κτιρίων

- Όπου οι αίθουσες είναι νότιες, επειδή συνήθως τα κουφώματα καταλαμβάνουν όλο το μήκος της εξωτερικής πλευράς τους, δεν είναι δυνατόν να εφαρμοστούν ηλιακοί τοίχοι (μικρό ύψος). Μπορούν όμως να προστεθούν ηλιακοί χώροι ή θερμοσιφωνικά πανέλα, μέσω των οποίων προθερμαίνεται ο αέρας του απαιτούμενου αερισμού των αιθουσών (5 φορές/ώρα). Στοιχεία για την μείωση του θερμικού φορτίου σε σχέση με τα πανέλα δεν υπάρχουν.
- Δροσισμός με αερισμό, όπου : Η μείωση θερμικού φορτίου για τη ζώνη Β: 63% - 81%, για τη ζώνη Γ: 55% - 79%
- Σκιασμός, όπου: Η μείωση θερμικού φορτίου για τη ζώνη Β είναι 20% και για τη ζώνη Α κυμαίνεται μεταξύ 12% - 37%.

Στις κατηγορίες αυτές πρέπει ακόμα να παρατηρηθεί και να ληφθεί σοβαρά υπόψη η υψηλή πιθανότητα μη καταλληλότητας του σκελετού από οπλισμένα σκυρόδεμα. Και αυτό σε συνδυασμό σε συνδυασμό της γνωστής διαδικασίας εξασθένησης αυτού από ενανθράκωση και οξείδωση του οπλισμού του με το γεγονός ότι μελετήθηκε με (αντισεισμικές κυρίως) παραδοχές, πολύ διαφορετικές από τα σημερινά αποδεκτά όρια.
Οι συνήθεις προκατασκευασμένες ενισχύσεις του σκελετού από οπλισμένο σκυρόδεμα πάλι με προσθήκη λεπτότερων στοιχείων του ίδιου δομικού υλικού, εκτός του γεγονότος ότι μπορεί να παραποιήσουν όποια τυχόν αισθητική αξία, είναι βραχύβιες και έχουν πολύ υψηλό κόστος.

Κατηγοτία 3: Κτίρια μετά '80

Εδώ ανήκουν τα σχολικά κτίρια που χτίστηκαν μετά τον κανονισμό Θερμομόνωσης.
Τα κτίρια αυτά παρουσιάζουν τα παρακάτω προβλήματα:

- Η θερμομόνωση (κυρίως πολυουραιθάνη και φελιζόλ) καλύπτει μόνο έως 30% του κελύφους. Η υπόλοιπη επιφάνειά του είτε δημιουργεί θερμογέφυρες (όλες οι πλάκες, οι δοκοί, τα διαζώματα, τα υποστυλώματα και τα προστατευτικά στέγαστρα των κουφωμάτων δεν έχουν μόνωση και αποτελούν το μεγαλύτερο ποσοστό των συμπαγών στοιχείων του κελύφους), είτε καλύπτεται από κουφώματα.
- Οι διαφανείς επιφάνειες είναι πολύ μεγάλες και ιδιαίτερα επιβαρυντικές στην περίπτωση που βλέπουν προς Βορρά.
- Ακριβώς επειδή οι διαφανείς επιφάνειες έχουν αυξηθεί σε έκταση χωρίς όμως, συνήθως, καμιά προστασία σκίασης, ούτε με προσεκτική επιλογή προσανατολισμού αλλά, κυρίως, με μορφολογικά (ή και μορφοκρατικά) κριτήρια επιλογής σχεδιασμού, παρατηρείται μεγάλο πρόβλημα υπερφωτισμού και, κυρίως,

υπερθέρμανσης, ακόμα και τις, όλο και συχνότερα παρουσιαζόμενες, ηλιόλουστες χειμερινές ημέρες.

Για τις παρεμβάσεις στα υφιστάμενα σχολεία απαιτείται ειδική μελέτη, που να λαμβάνει υπόψη της τις νέες απαιτήσεις.

Οι σχολικές αίθουσες, σύμφωνα και με τις προδιαγραφές του Ο.Σ.Κ., έχουν ανάγκη συχνού αερισμού. Είναι σημαντικό η θέρμανση τους να στηρίζεται κυρίως στην ακτινοβολία των δομικών στοιχείων και όχι τόσο στην θέρμανση του αέρα, ο οποίος εναλλάσσεται πολύ συχνά. Έτσι έχουν προτεραιότητα οι μέθοδοι θέρμανσης που διοχετεύουν τη θερμική ενέργεια σε τοίχους, δάπεδα και οροφές με πηγή θερμότητας είτε με συμβατικά είτε με παθητικά ηλιακά συστήματα θέρμανσης.

Επίσης είναι αναγκαίο να μελετηθούν μέθοδοι προθέρμανσης του φρέσκου αέρα που εισέρχεται στις αίθουσες. Τα παραπάνω στοιχεία προτείνονται με την προϋπόθεση του ευνοϊκού (νότιου) προσανατολισμού.

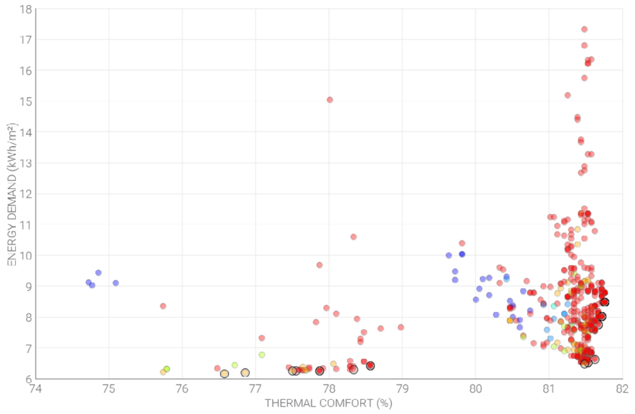
Οι επεμβάσεις που αναφέρθηκαν είναι υλοποιήσιμες σε υφιστάμενα σχολεία γιατί αφενός, είναι σχετικά τυποποιημένα σε σχέση με τα δημόσια κτίρια γραφείων ή άλλα κοινωφελή κτίρια και αφετέρου, γιατί είναι προσφορότερες επεμβάσεις, εφόσον βρίσκονται συνήθως σε ελεύθερα γήπεδα. Το πρόβλημα δε, της σχολικής στέγης τείνει να καλυφθεί πολύ σύντομα και στο μέλλον θα έχουμε μικρό ποσοστό νεοαναγειρόμενων σχολικών κτιρίων.

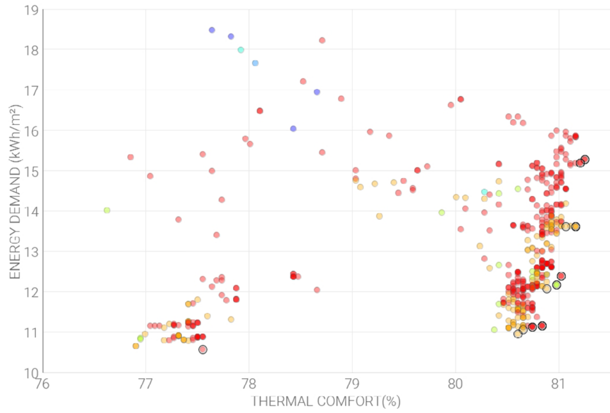
APPENDIX B:

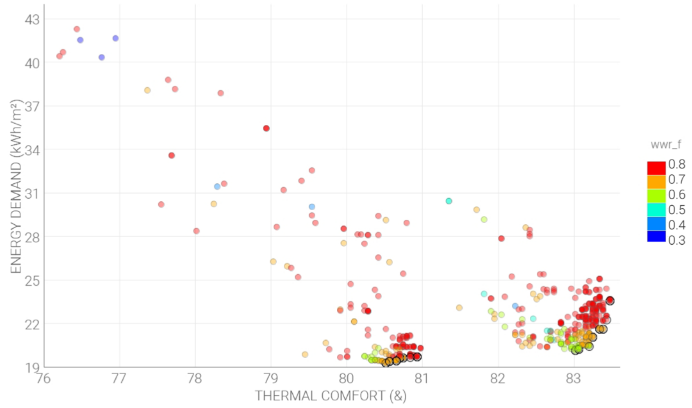
Overview of the distribution of the designs for 8 optimizations variables, for the three climate zones, with regards to the two defined objectives (Thermal Comfort on the x axis and Energy Demand on the y axis), as exported from modeFRONTIER.

ZONE A | **ZONE B** | **ZONE C**

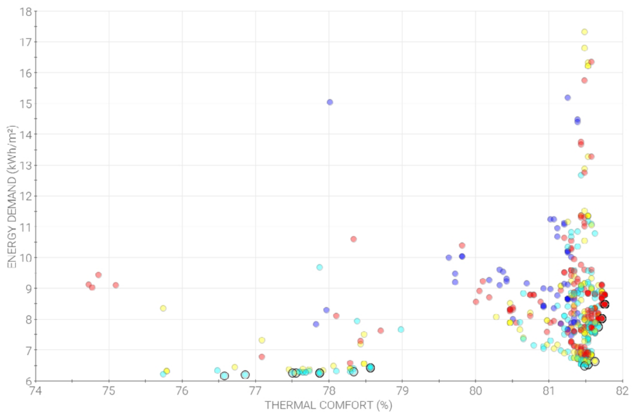
wwr_f

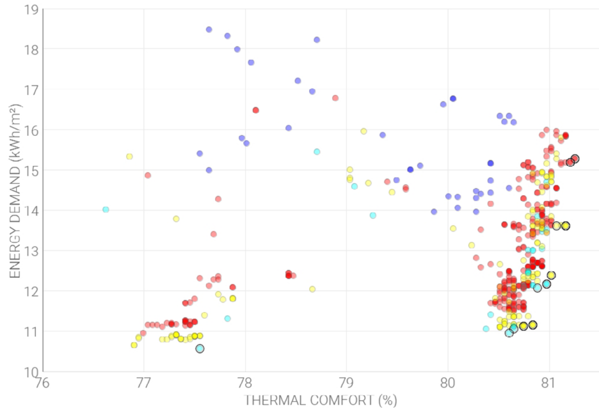


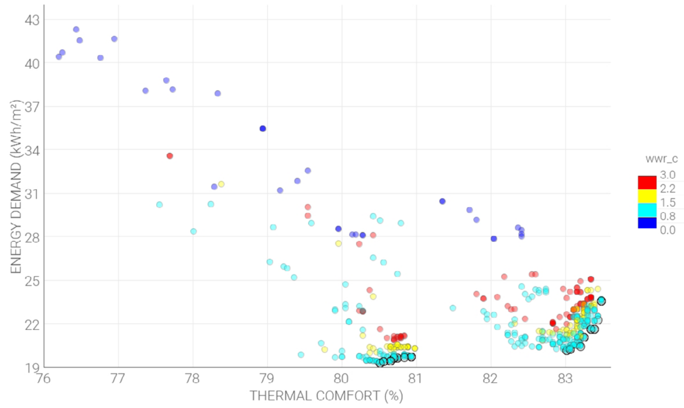




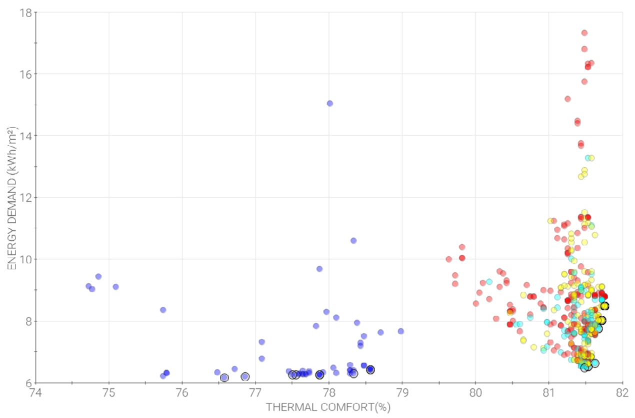
wwr_c

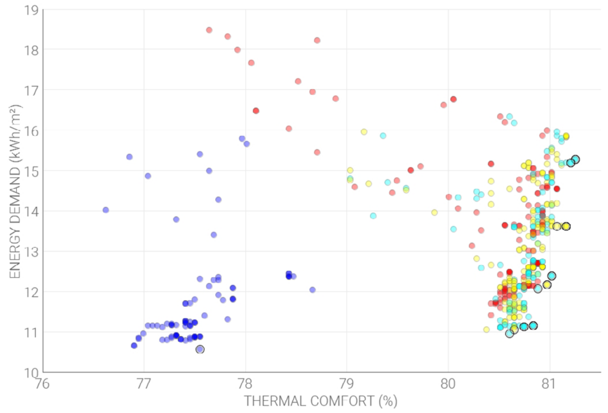


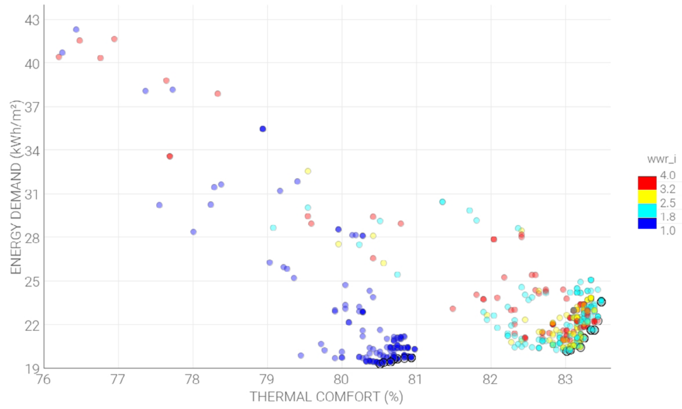




wwr_i







ZONE A | ZONE B | ZONE C

VT

SHGC

shading type