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"Parametric analysis & performance optimization of passive solar sunspaces under different European climates"

Papakostas Ioannis

SID: 304170006

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Building Design

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Abstract

The dissertation is part of the Msc in Energy Building Design program of the International Hellenic University of Thessaloniki, under the supervision of the professor Dr. Theodoros Theodosiou. The aim is to investigate the energy behavior and main operating principles of the passive solar sunspace.

The first part of the paper consists of a short literature review of previous research on passive sunspace systems. It analyzes the typology of different passive sunspaces systems, the different design variations, their materials and components and the various design options that affect its operation. The advantages of using passive solar systems instead of conventional and energy conservation techniques in residential buildings will be highlighted.

The scope of the paper is to study and evaluate the thermal performance of the sunspace and try to determine the key factors that affect it. A series energy simulation will analyze the effect of different parameters such as the materials, shapes, orientations, thermal coupling with the building, and operations parameters (movable insulation etc.) together with representative climate parameters across the European continent, in order to propose an effective design optimization. The simulations are representative of the prevailing conditions throughout Europe and deal with a wide range of them.

The software that will be used is SketchUp for modeling and EnergyPlus for the energy simulations. Every simulation, for all the parameters tested, will be accompanied by a report of the results in the form of chart and diagrams. The comparison of the results produce will eventually lead to the formation of the design guidelines.

Papakostas Ioannis

02/01/2020

Contents

1 Introduction

Oil and coal are the two most conventional sources primary energy sources. Like all the non-renewable sources, the reserves are limited and they will soon get exhausted. Moreover, fossil fuels are one of the main causes of environmental pollution and the greenhouse phenomenon, since the emissions of the carbon dioxide produced during its consumption are very high. (Axarli, 2008). It is widely accepted that our dependence on fossil fuels will be gradually reduced during the forthcoming years, thus it is essential to improve the energy efficiency of the building sector, using alternative sources of energy (Bataineh and Fayez, 2011).

The building sector is one of the most significant energy consumers. It is calculated the 41% of the total production, in European Union countries, is spent to meet the heating and cooling needs, as well as the operation needs of the buildings (hot water, electrical appliances, lighting etc.).

Sustainable development is a term that has been proposed as an alternative model to face the negative effects of environmental pollution. International, European and national legislation have shaped a legislative framework that promotes energy saving technologies and techniques in order to mitigate the effects on the environment. Renewable sources are thought to be a never exhausting supply of energy that can be considered as a solution. The use of use of solar, wind geothermal energy can be used to cover part or the whole of the building's thermal and cooling loads and at the same time minimize the use of fossil fuels.(Axarli, 2008)

The EU has introduced since the early 2000s guidelines and regulations that drive countries towards buildings with minimum energy requirements, low energy consumptions and low emissions.(Ulpiani *et al.*, 2017) According to the 2010/31/EU Directive on the energy performance of building (EPDB) by the year 2020 all new buildings have to be “nearly zero-energy buildings”. In order to meet the requirements of the goal it is crucial to reduce the heating and cooling demand by utilizing solar energy through passive or active solar systems.(Sánchez-Ostiz *et al.*, 2014)All the above should be integrated into the energy design of the buildings without any compromise concerning the visual and thermal comfort of the users.

An important parameter that constantly pushes the limits of energy efficiency is the new material research. New material and product development are able to improve the thermal performance of the buildings and the indoor conditions. The two areas with the highest effect and the potential for improvement is the glazing and the aperture materials. The can not only control the amount of solar radiation that will become available to the solar system but at the same time they can reduce heat losses. They can act like a skin that is responsible for the energy balance of a building.(Balcomb, 1984)

Thermal equilibrium

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI, ASHRAE Standard 55). The air temperature of a room is one of the factors that can affect thermal comfort and is directly related to other parameters like the activity performed in space, the age, the clothing etc. The fluctuation of the desire air temperature is achieved by the heating or cooling mechanisms. The smaller the need for heating and cooling the more energy saving the building becomes. (Axarli, 2008)

The total heat gains and losses of the building define the thermal equilibrium. The temperature difference between the interior of the building and the exterior causes thermal flows that happen both ways.

Thermal comfort

The feel of thermal comfort is achieved when an individual is in a thermal equilibrium with its surroundings. That means that the body can unleash the right amount of heat to the environment. In cases of stress, when the environment is cold or very hot the body either unleashes more or cannot unleash the extra heat, so it cannot achieve thermal comfort. The zone of thermal comfort is defined by six correlated physical parameters, the temperature of air, the mean radiant temperature, the clothing insulation, the metabolic rate, the air speed and the relative humidity. Some of them (clothing insulation and metabolic rate) are categorized as personal factors and he others as environmental factors.

When it comes to bioclimatic buildings the most important parameter in achieving thermal comfort conditions is the envelope, that acts like the skin. It can interact with the surrounding environment so that can create the best possible thermal comfort conditions for users and the lowest possible consumption for heating and cooling.(Axarli, 2008). During heating period, the aim is to minimize thermal losses produce by conductivity, ventilation and evaporation while at the same time to increase heat gains in order to reduce the heating demands. Similarly, during cooling period, the plan is to reduce thermal gains produced from solar radiation and to optimize the ventilation and natural cooling techniques. In general, solar is the most popular renewable energy source, especially in countries with high solar potential, as the technology has made a great progress in terms of efficiency and production cost.

The solar systems are categorized into two main categories, the passive and the active systems. Passive solar systems take advantage of the solar radiation in order to cover part of the heating or cooling needs of a building without making any use of other mechanical systems. Their operation is based in the natural flow of heat and the properties of the materials used. Active systems make use of mechanical means (pumps, fans) either to store or circulate heat produce by the sunspace. (Axarli, 2008)

Passive solar systems are considered to be energy systems that can significantly contribute to a building's energy efficiency, especially during winter. Among all systems, sunspaces are considered to be an attractive technique due to their simplicity, low cost and soft adaptation to existing facades.

2 Passive solar Sunspace

Sunspaces are considered to be one of the most popular passive solar design options. This opinion is backed by a numerous of calculations and monitoring performed, related to their energy performance. Their flexibility and versatility offer many possibilities for integration into the architectural design. Sunspaces is a useful architectural tool that can produce new architectural dimensions, both in the both in the primary stages of the design of the buildings and in numerous retrofitting cases.

The primary role of passive sunspace systems is to collect as much energy as possible, transform it in to heat and guide it towards the living areas. (Protic, 2018) . The sunspace area acts as a buffer zone between the environment and the treated area, the main residence. In terms of space usage, the sunspace can be a fully operating part of the residence like a patio, a hallway or an entrance or it can be used supplementary to the residence main space as a greenhouse full of plants. Whether the sunspace is considered a main residence area or not, it does not effect is thermal behavior regarding its relation to the treated area. Practically it is intermediate space, a transition between the interior and the outdoor environment which can be designed in any way to meet the everyday needs of the occupants, while being a primary heat source during winter. It is up to the architect or the designer to create a space that can accomplish both (Robert W. Jones, 1984)

In climates with not a cold winter or a hot summer that is not the case since they can easily achieve interior conditions of comfort. In contrary in climates where the sunspace work as solar heating system appropriate measures have to be taken to avoid overheating. The key to achieve that is a good thermal design of the sunspace area.(Monge-Barrio and Sánchez-Ostiz, 2015). The overheating issue can be dealt with by the following solutions:

- Shading devices, who can allow the useful solar energy to enter the sunspace during winter and protect the area from overheating during summer.
- Night ventilation accompanied with the appropriate thermal mass material properties. A well-insulated thermal mass wall can store the excess energy produced during the day and release it during ventilation at night.
- Buried pipes, taking advantage of the temperature difference between the sunspace area and the ground.

- A scenario that mixes two or all the above techniques to achieve even higher efficiency(Mihalakakou, 2002).

In climates with cold winter but warm or hot summer, since in areas with a cool summer it is not necessary because there are already exterior conditions of comfort. In climates where sunspaces work as a solar heating sys-tem in winter, the approach is that they should not contribute to overheating in the housing in summer, and if they do, measures to prevent this are proposed. Passive systems should always be designed according to the local climate conditions and urban planning context. In summary, optimized solutions are looked for throughout the year. (Petrović, 2019)

Sunspace typologies

There are several types of typologies and they are classified depending on how the sunlight is collected and then accumulated to the adjacent room, the type of the heat transfer medium, the geometry and its positioning in relation the building and the position, size and type of the thermal mass.(Vasovic, 2018)

2.1 Sunspace operation

A sunspace room is usually an area enclosed by large windows to admit sunlight. The room collects, stores and distributes heat to the adjacent rooms. The attached sunspace is a combination of a direct gain system and a thermal mass (wall) system. The sunspace or greenhouse is usually built on the south side of the building and it has at least one and up to three of its sided made of glass. The sunspace interconnects with the main building through a thermal mass wall, which is usually the heat store and transfer medium. (Axarli, 2008) The sunspace can be integrated at the early stages of the original design or even added to an existing building during a retrofit.

The greenhouse effect

The greenhouse effect is the main pillar where the sunspace operation is based. The concept is that sun rays passing through glass surfaces are captured and produce heat. Glass elements have the properties to be permeable to the short wave radiation of the sun rays (0,4-0,25 microns) while at the same time to be impermeable to the thermal radiation emitted by the opaque elements which has a wavelength of about microns. Therefore, a big portion of the solar radiation that enters a sunspace, (a percentage of sunlight is reflected or absorbed by the glass surface), is transformed into thermal radiation and trapped into it.

An essential requirement for a heat production and distributing solar system to be considered passive is to perform all its operations without the use of mechanical or electrical equipment. Otherwise, when any sort of mechanical or electrical equipment is used to perform any function, the system is called active.

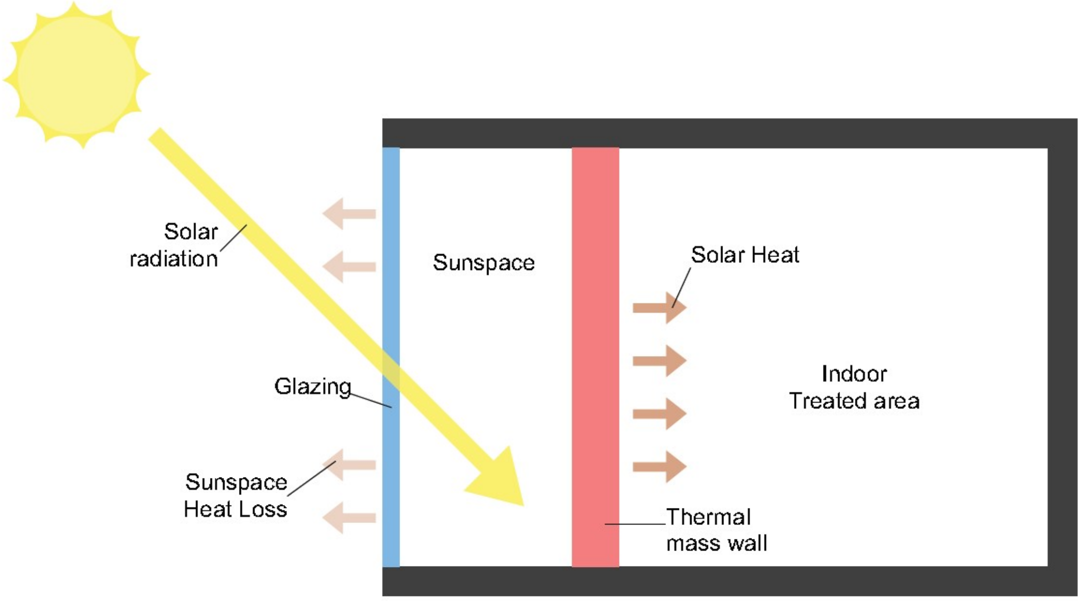


Figure 1 . Sunspace operation scheme

The operation of the solar sunspace (figure 1), just like almost all the passive solar system can be described by the following terms:

- Solar energy
- Glazing
- Heat storage
- Heat Conservation
- Controls

2.2 Solar energy

There are three types of solar radiation that can become available for a sunspace to exploit, the direct, the diffuse and the reflected one. The direct radiation comes direct from the sun without any scattering from the atmosphere. When there are no clouds on the sky, most of the solar radiation available is direct. The diffuse is the solar radiation that can reach a sunspace after being scattered by the atmosphere of the earth. Its direction cannot be known as it arrives from the sky indefinable. Diffuse radiation is the most common one when there is overcast. The reflected radiation is direct or diffuse radiation that has reached the surface of the earth and it has been reflected by the ground, the buildings or any other object. (Robert W. Jones, 1984)

2.2.1 Direct radiation

Direct solar radiation has the highest effect on solar passive systems out of the three solar radiation types available, especially when there is no overcast. Perhaps the most important feature of direct solar radiation, that can determine the design of a sunspace is the direction, which is related to the sun's position, the clearness of the weather, the latitude of the area, the time of the day and the glazing orientation. The total direct solar radiation available for a sunspace, is deeply related to the location of the sunspace, the prevailing climatic conditions of the area and of course the orientation of the windows area. (Robert W. Jones, 1984)

The effect of the glazing

The term glazing refers to the material that the sunspace windows are med of. The most common material is the glass, although there are also plastic derivatives that can be used instead. The glazing is responsible for two main procedure of the sunspace operation. First through the glazing transmits the solar radiation into the sunspace area. So it is responsible for the solar gains. The glazing also affects the amount of heat that is transmitted back to the environment, or else the heat losses. (Robert W. Jones, 1984)

Transmittance

Not all of the direct solar radiation that reached the glazing surface is exploited. Only a portion of it passes through or is transmitted. Some of it is bounced backed to the atmosphere, or is reflected, and some is absorbed by the glazing material. The radiation that is neither reflected or absorbed is transmitted (figure 2). Usually, transmittance of the glazing is higher at normal incidence and close to zero at a 90-degree angle of incidence. (Robert W. Jones, 1984)

Different materials have different transitivity levels for the various wavelengths of the solar radiation. What interests more regarding the glazing is the shortwave that refers to the solar and the longwave that refers to the thermal range. Most of the glazing materials have high shortwave transmittance in order to allow the biggest portion of solar radiation to enter the sunspace and low longwave transmittance to trap the heat in the sunspace area and reduce heat losses. (Robert W. Jones, 1984)

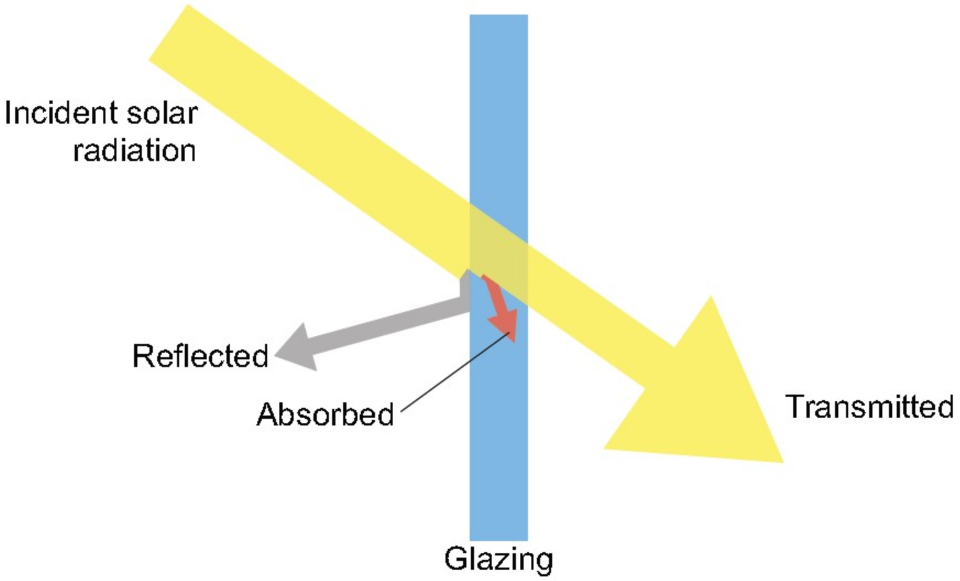


Figure 2 . Transmittance of solar radiation through the glazing

Translucency and Transparency

The glazing id the sunspace can also diffuse the solar radiation that transmits. The diffusion of solar radiation creates a fuzzy view through the glazing, so translucent materials are the best choice when intimacy is the issue. Furthermore, diffusion means that the radiation that enters the sunspace is scattered and distributed evenly in all the sunspace surfaces, avoiding areas of overheating that can be the case with the transparent glazing. (Robert W. Jones, 1984)

Reflection - Absorption

A portion of the solar radiation that reaches the surface of the glazing does not enter and is reflected back to the environment. The amount of the reflected radiation is a fraction of the incident radiation and it is called reflectance. Two main parameters can affect the reflectance, the material and the angle of incidence. The reflectance is smaller at a normal incidence and raises towards the angle of 90 degrees, where almost all radiation gets reflected. (Robert W. Jones, 1984)

Another portion of the incident solar radiation that does not enter the sunspace is absorbed by the various layers of the glazing. Although, the radiation absorbed is not considered a total loss, since it helps to raise the temperature of the glazing decreasing the heat losses from the sunspace envelope. Although, the transmitted radiation is more useful to the general behavior of the sunspace than the one absorbed. (Robert W. Jones, 1984)

The absorptance of the glazing depends on its materials and the angle of incidence of the solar radiation. The radiation travels through the layers, before transmitted to the sunspace. The thicker the glazing layers the higher the absorptance. Since absorption depends on the distance that the radiation travels through the glazing, it is less at normal incidence radiation and higher close to 90 degree angles. (Robert W. Jones, 1984)

Multiple Glazing

Often the glazing consists of two or more layers. The use of more than on layers helps reducing the heat losses as the gap between the layers, usually air, acts like insulation. However, since the transmittance is connected to the absorptance and the reflectance of the glazing, by raising the glazing layers the transmittance gets lower. Thus, even if the heat losses reduce at the same time the heat gains also are negatively affected. (Robert W. Jones, 1984)

Orientation

Every sunspace design aims to the maximization of the amount of solar radiation transmitted through its windows. As described above, at normal incidence the losses due to absorption and reflection are minimum while the transmittance levels are the optimal ones. Thus, in order to achieve optimization in design the glazing has to be perpendicular to the radiation received at any time. However, that cannot be achieved in an absolute way since the direct, diffused and reflected radiation come from different directions which is in a constant change. Although, there are some ground rules that can be applied, concerning the orientation of the glazing, that can help achieve optimum performance. (Robert W. Jones, 1984)

The *azimuth* and the *tilt* are the two angles that define the glazing orientation. The *azimuth* is the angle formed between the glazing and the horizontal line from East to west. The zero azimuth means that the glazing is facing the true North, which is the optimum direction when design a sunspace. A small deviation from the zero-degree azimuth does not alter substantial the solar heating performance of the sunspace, although a deviation more than 45 degrees either towards East or West can dramatically decrease the solar thermal gains. Moreover, the heat losses are higher from an eastern or western window compared to a southern one. High deviations from the zero azimuth can have a negative effect not only during winter but also during summer when heat gains are undesirable. An East or West facing window can cause problems of overheating, especially when not properly shaded. However, the South orientation cannot always be achieved due to constraints that relate to the shading cause by adjacent buildings or trees, the topography of the site or the orientation of the existing building when the sunspace is part of a retrofitting. (Robert W. Jones, 1984)

The other defining angle is the glazing *tilt* and is the angle formed by the glazing and the horizontal plane. There is not a standard rule on how to calculate the optimum glazing Tilt since it depends mainly on the latitude of the location, the local climate and the building needs. As an empirical rule it is widely used that the sunspace glazing title angle should follow the latitude angle with a small deviation of 20 degrees less or more without substantial effect on the performance. Although a sloped glazing on a sunspace is not always the optimum design choice. Since sunspaces mainly aim to take advantage of the winter solar radiation to reduce the energy needs for heating a vertical glazing is much more efficient that a sloped one. Moreover, overheating problems are more likely to occur to a sloped glazing during the summer period compared to a vertical glazing. (Robert W. Jones, 1984)

2.2.2 Heat storage

In order for the solar radiation that has been transmitted through the glazing to become useful, it has to be absorbed by the sunspace interior surfaces. The interior surfaces raise their temperature by converting solar radiation into heat. The heat absorbed during daytime, has to be stored and then released to the adjoining building during the night, when the temperature drops and the solar radiation is absent. This way some of the buildings heat energy requirement is covered by the solar radiation absorbed and then released by the sunspace surfaces in the form of heat. These procedures can describe the daily cycle of heat storage. (Robert W. Jones, 1984)

Heat storage can also help in maintaining the conditions in the sunspace inside the thermal comfort boundaries, which is very useful especially in the case where the sunspace is part of the habitable area. By absorbing a portion of the solar heat during daylight helps to moderate the very extreme temperature during the day while the temperature at nigh is higher than the outdoor because the stored heat is released. Furthermore, heat storage is a way to determine the amount of solar radiation that will be used immediately to heat up the air and the amount that will be stored and used for heating the adjacent air at a later point. (Robert W. Jones, 1984)

Basic operation principles of the heat storage procedure

The first phase of the heat storage procedure is the solar radiation absorption. Radiation strikes the heat storage medium surfaces and its transformed into heat. Consequently, the ability of the store media to absorb a fraction of the solar radiation defines its effectiveness. The surface colour and texture are the two main parameters that affect the absorptance. Dark colored surfaces in general absorb higher portion of solar radiation than light colored. Absorptance, although, does not depend only on the surface colour but also on the geometry of the sunspace. The sunspace, taking advantage of the cavity effect, can act like a trap, capturing the solar radiation that has entered through the glazing. The radiation has not been absorbed by the first surface is reflected and absorbed by another surface of the sunspace. Thus the more opportunities for the solar radiation to be absorbed the higher the effectiveness of the sunspace. (Robert W. Jones, 1984)

Heat storage mediums

All the sunspace surfaces that are directly or indirectly illuminated by a component of solar radiation can be considered as a heat storage medium. The effectiveness is higher when the direct radiation strikes a surface, so the sunspace floor or the north (common) wall with the adjoining room are the preferable locations for the heat storage to take place. The East and West walls can also be used, although they do not receive direct radiation during the most of the day. It is important in the early both in the early design and during the use of the sunspace area to avoid any shading on the heat storage medium. (Robert W. Jones, 1984)

Except direct or diffuse solar radiation the heat storage medium can also raise it temperature by receiving thermal radiation emitted by other warm sunspace surfaces. In order for two surfaces two exchange heat by thermal radiation there has to be no obstacle between them. Furthermore, heat can be transferred to the storage medium thought the process of convection. The warm surfaces heat the air which rises and is replace by the cooler air resulting in an air circulation that transfers heat from the warmer to the cooler surfaces of the sunspace. (Robert W. Jones, 1984)

The two most common used materials are the concrete for both the slabs and the wall and the brick for the masonry. In order for a storage medium to be effective it has to fulfill two requirements. First it has to be capable of storing heat and second to be able to receive and emit it easily. The first is described by the term of heat capacity and the second with the term of heat conductivity.

Heat capacity

Heat capacity is the physical property which is defined by the amount of heat needed in order for a mass to change its temperature by 1 unit. When the mass stores heat its temperature raises while it releases heat its temperature drops. This procedure is described as the sensible heat capacity, which is a substance of the heat capacity, although the two terms are often correlated.

Two other terms that describe the ability of a material to store heat is the specific heat and the volumetric heat capacity. The specific heat is the heat capacity expressed per unit of weight while the volumetric heat capacity is the specific heat multiplied by the density of the material.

Based on the above properties the most desirable materials that can be used in heat storage walls are the concrete, brick, stone and the most effective one water, although constructions with water as masonry material are unconventional. On the other hand, insulative material such as the extruded polystyrene should be avoided due to their low volumetric heat capacity. (Robert W. Jones, 1984)

Thermal Conductivity

In order for the heat to get stored in a body, it needs to be transferred from the outside surface through its body. Heat always flows from a hotter to a colder body. So, when the solar radiation strikes the surface of the heat storage medium it gets warm, while the its interior remains cool. So the heat needs to travel through its body, before eventually released to the adjacent room. (Robert W. Jones, 1984)

In solid elements the heat flow takes place mainly through conduction. The ability of a material to conduct heat is called thermal conductivity. Materials with high thermal conductivity are used at heat sink applications while material with low thermal conductivity are used as thermal insulators.

Masonry

The masonry used at a sunspace for heat storage needs to have both high heat capacity and thermal conductivity. The material used are usually concrete, brick or stone which all have good thermal characteristics. The masonry has to be as solid as possible with no voids interfering between the masonry layers, since the voids act like insulators since they have no actual heat capacity and prevent the heat flow between the layers. (Robert W. Jones, 1984)

Masonry thickness

The masonry needs to have a specific thickness in order to become useful and contribute to the reduction of the heating needs of the adjacent room. The ideal day cycle of the hat storage wall should be like the following. During daytime the heat flows from the exterior surface towards its inner core, while some of it is released back to the sunspace area. During nighttime. on the other hand, the stored heat is released both to the adjacent space and the sunspace area (figure 3). If the masonry is not thick enough, then there will not be sufficient material to store enough heat and if the masonry is thicker than needed the heat will never flow throughout the thickness of the wall and will never reach the interior surface and be released. (Robert W. Jones, 1984)

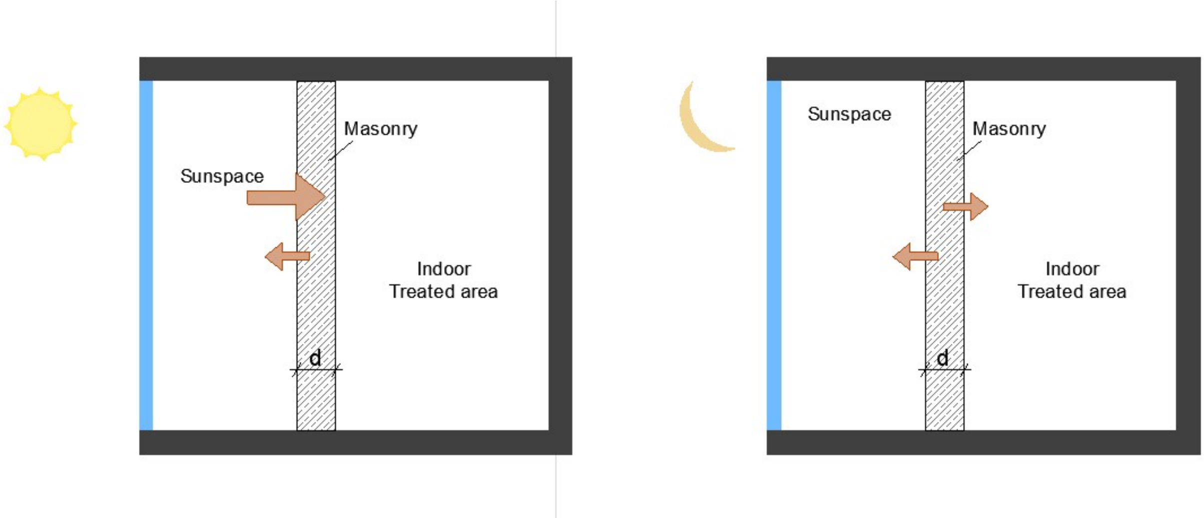


Figure 3. Masonry heat release during daytime and during nighttime.

As described the stored heat can be emitted either by the sunspace the wall surface at the side of the sunspace or the surface at the side of the adjacent room. Both portions are determined by the thickness and the material of the thermal mass wall. The optimum thickness is the one that offers the proper delay between the heat storage during the daytime and the heat release to the adjacent rooms during nighttime. (Robert W. Jones, 1984)

Water containers

An effective and very common way to store heat, especially in a retrofitting, are the water containers. The heat capacity of the water is higher than the materials used in masonry so they can absorb and utilize higher amounts of solar heat. Another advantage of the water containers is that all the volume of the water is useful, meaning that there is no need for special design or complicated calculations. The more the water volume the more heat will be stored. They absorb the excess eat produce during the day and then release it as soon as the air surrounding the tanks gets cooler than the water in them.

Figure 4. Solar storage water tubes.
Source: http://www.solar-components.com/TUBES.HTM

2.2.3 Heat conservation

The efficiency of the sunspace design is not only determined by the amount of solar energy that stores and distributes to the adjoining building but also by the degree of energy conservation they provide. As any other conventional part of a building a sunspace has heat losses through the envelope that indirectly affect the energy behaviour of the adjacent building. The higher the sunspace heat losses, the less energy is delivered to the building. Consequently, energy conservations measures are of high importance in terms of the sunspace efficiency as a heat source. Heat losses in a sunspace happen in various ways and forms (figure 5), although the most common are the heat losses through the glazing, the infiltration, the exfiltration and the conduction heat losses through its opaque surfaces like the walls, the floor and the ceiling. (Robert W. Jones, 1984)

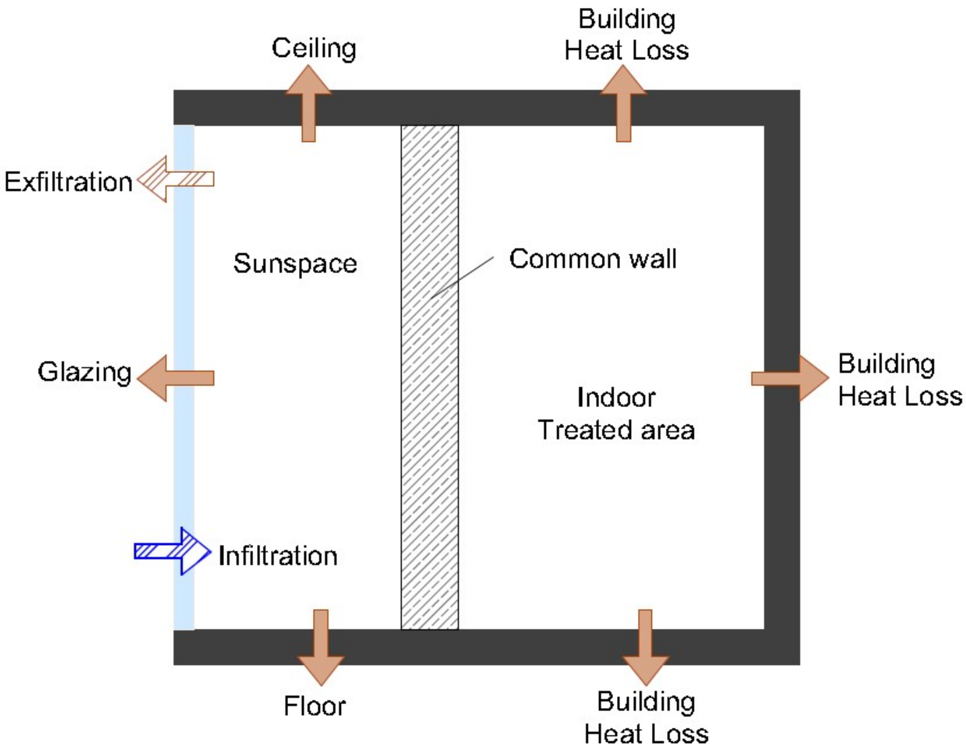


Figure 5. Sunspace and building heat losses

Sunspace heat losses - Convection

Sunspace heat losses could happen thought the processes of convection, conduction and radiation. Convection heat losses occur mainly due to the contact of the warm air that flows in the sunspace with the cool interior surface of the glazing. Subsequently the heat flows to the exterior surface of the glazing before eventually released to the outdoor environment. That way, a portion of the solar radiation that was transformed into heat never reaches the adjacent building but is emitted back to the environment. The same process applies for the opaque surfaces of the sunspace, although the heat losses are substantially lower. (Robert W. Jones, 1984)

Radiation heat losses

Solar radiation heats the opaque surfaces of the sunspace which raised their temperature. The opaque surfaces emit thermal, longwave, radiation that strikes the glazing and the other opaque surface across the area. Although not all the emitted radiation is considered to be heat losses since a portion of it is absorbed and radiated back to the sunspace area in a vicious circle. Nevertheless, radiation heat losses, and especially through the glazing are a significant contributor to the general sunspace heat losses. A suitable solution of reducing the radiation heat losses would be measures that block the emitted radiation from reaching the glazing or the opaque surfaces or the use of material on the interior surface of the glazing with low long wave absorptivity and high longwave reflection. (Robert W. Jones, 1984)

Losses through the glazing

Most of the sunspace heat losses occur through he glazing since not only the occupy most of the sunspace envelope but also because the glazing materials have low resistance to heat losses. The resistance of a surface to the heat flow is described by its R Value. The most common measure to increase heat flow resistance through the glazing is the use of double glazing that are separated by a thin layer of air. The air layer functions as insulation. In general, even insulation materials like the expanded polystyrene owe their high R values to the trapped air pores included in their body. The second glazing layer also reduces the infiltration rate in comparison to the single glazing and consequently reduce the heat losses. (Robert W. Jones, 1984)

The double glazing offers improved resistance to heat losses but at the same time the second layer of glazing decreases the transmissivity. So the heat gains may be negatively affected as well as the overall energy behavior of the sunspace. Nevertheless, the advantages of the use of double glazing surpass any disadvantages, since they also offer additional protection against concentration, and the help into maintaining more stable and comfortable conditions inside the sunspace area by moderating the extremes, something that can be proved very useful in cases that the sunspace is used by the occupants as a living area or a greenhouse. (Robert W. Jones, 1984)

Opaque surfaces insulation

When common wall is the heat transfer medium between the sunspace and the adjoining room, it is preferable the use of no insulative layers, so that the heat flow to the interior is not imbedded. The addition of insulation to the other opaque surfaces of the sunspace, such as the walls, ceiling and floor can help into reducing the conduction heat losses and therefore the total energy behaviour. (Robert W. Jones, 1984)

Moveable insulation

Since the heat losses through the glazing represent the biggest portion of the sunspace heat losses, the use of moveable insulation can be proven an effective solution. The insulation can be placed during the nighttime, outside or inside the sunspace glazing in order to prevent the heat flow to the exterior and therefore capitalizing higher amount of the stored heat produced during daytime. During the daytime the insulation can be removed and the energy performance of the sunspace remains unaffected. Moveable insulation can be also used during summer period in order to block the solar radiation from entering the sunspace and avoiding overheating. (Robert W. Jones, 1984)

2.2.4 Heat distribution

Passive solar sunspace are indirect systems since the heat is produced in the sunspace and then has to be delivered to the adjoining room through a medium. One way to deliver the heat is the common wall, which depending to is constructions and characteristics can regulate the heat flow from the sunspace to the building and vice versa and can help into achieving the desire indoor conditions. (Robert W. Jones, 1984)

An insulated common wall can isolate the two parts of the system, the adjacent building and the sunspace, so the heat flow can only happen through openings, windows or vents that can be controlled by the users. That way both heat gains and heat losses occur only when needed. On the other hand, when an uninsulated wall is applied, the heat flow through the common wall is a constant procedure and the designers has to consider and incorporate its thermal characteristics to the general design of the sunspace in order to maximize the sunspace efficiency. In any case, both with an insulated or uninsulated wall is applied the heat transfer can happen be entirely passive without the use of mechanical means. (Robert W. Jones, 1984)

Sunspace integration

The way the heat flows between the spaces is directly dependent to the integration level of the sunspace. There are various ways and degrees that a sunspace can be integrated into a building. Of course, in a retrofitting case the options are limited since there is no room for intervening to the existing building. In that case the sunspace is attached to it and they usually share one common wall. In cases where the sunspace is part of the original design of the building they can share two, three walls or even be entirely integrated in it like an atrium and the glazing is placed on the roof. The more the walls the two spaces share the most the surface available for heat distribution to the adjoining room, more heat storage that can become available when needed and less the heat losses from the sunspace exterior walls. (Robert W. Jones, 1984)

Heat transfer

The main heat transfer happens by conduction through the common walls. The material and the thickness determine the time delay and the intensity of the heat transfer throughout the day. A thin wall will deliver heat earlier during the day, mainly during the early evening and for less hours, causing problems of overheating. A thicker will deliver a higher amount of heat, spread in more hours later evening or even during night. (Robert W. Jones, 1984)

Heat transfer may occur by air circulation through the openings also and can sometimes be greater than the heat transfer by conduction. The openings can take the form of doors, windows or vent airs. The air vents take advantage of the natural flow of air. They are placed in pairs, one near the floor and the other near the ceiling. The warm air rises while the cooler sinks creating a continuous circulation between the sunspace and the adjoining room air. Windows can be used when the view to the sunspace or natural light are desirable. Although, they have some drawbacks regarding the energy performance of the sunspace. The emit transmit direct radiation to the adjoining rooms causing overheating and due to their low R value they contribute to the night heat losses. (Robert W. Jones, 1984)

Figure 6. Integer Millennium House built at Watford in 1997. The house was built according to the passive solar design principles including a wedge shaped south facing attached sunspace. *Source*: http://www.greenspec.co.uk/buildingdesign/designing-for-passive-solar/*

Figure 7 . Integrated sunspace of a detached single family Passive House in Volos, Greece designed by Stefan Thomas Chatzoulis/XG group of engineers in 2017

3 Research methodology

Introduction

The scope of the study is to create a guidance for performance based generative design for sunspaces, by conducting a series of energy simulations that study the key factors that affect its energy performance. In performance based generative design, the energy performance of the building is the central pillar, around which every decision about the form, the geometry, the orientation, the construction and envelope materials and the operation schedule are taken. The procedure can be described as a discomposure of the design process into subcategories that lead to a number of solutions, based on facts. This pool of optimized solutions will eventually lead to the final design of the of the sunspace.(Touloupaki and Theodosiou, 2017b)

During the last decades The design process has been drastically altered due to the technological advances. New tools have been created that can address multiple tasks at the same time. The energy performance analysis and simulation of the building is becoming a major design factor, offering new capabilities and perspectives to the designer. The architects' initiatives and intentions are being replaced by data driven decisions pushing the creation process towards into computational design. (Touloupaki and Theodosiou, 2017a)

Methodology

The method that will help to investigate the key parameters that affect the energy behave of the passive solar sunspace is the isolation of the different building components, the running of energy simulation based on variations of their characteristics and then draw conclusions based on the analysis of the simulation results. These series of simulations can be divided into two main subcategories, each one of them testing examining different parameters, from which we can draw a variety of conclusions. The first set of energy simulations will examine all options concerning the design of the sunspace (size& shape, orientation, attachment relation to the reference building), the materiality (glazing, thermal mass of walls) and the operation schedule (moveable insulation, selective shading). The second will test all the above parameters under the different European climates in order to create a guideline of parameterization according to the local climate condition of each region.

The outcome of the energy simulation for every design option will be compared to the outcome of the energy simulation of the reference model in terms of heating, cooling and ventilation demand, as well as other parameters that may affect thermal comfort conditions on a case by case basis.

The general strategy, according to which the simulation procedure was structured, can be described by figure 8.

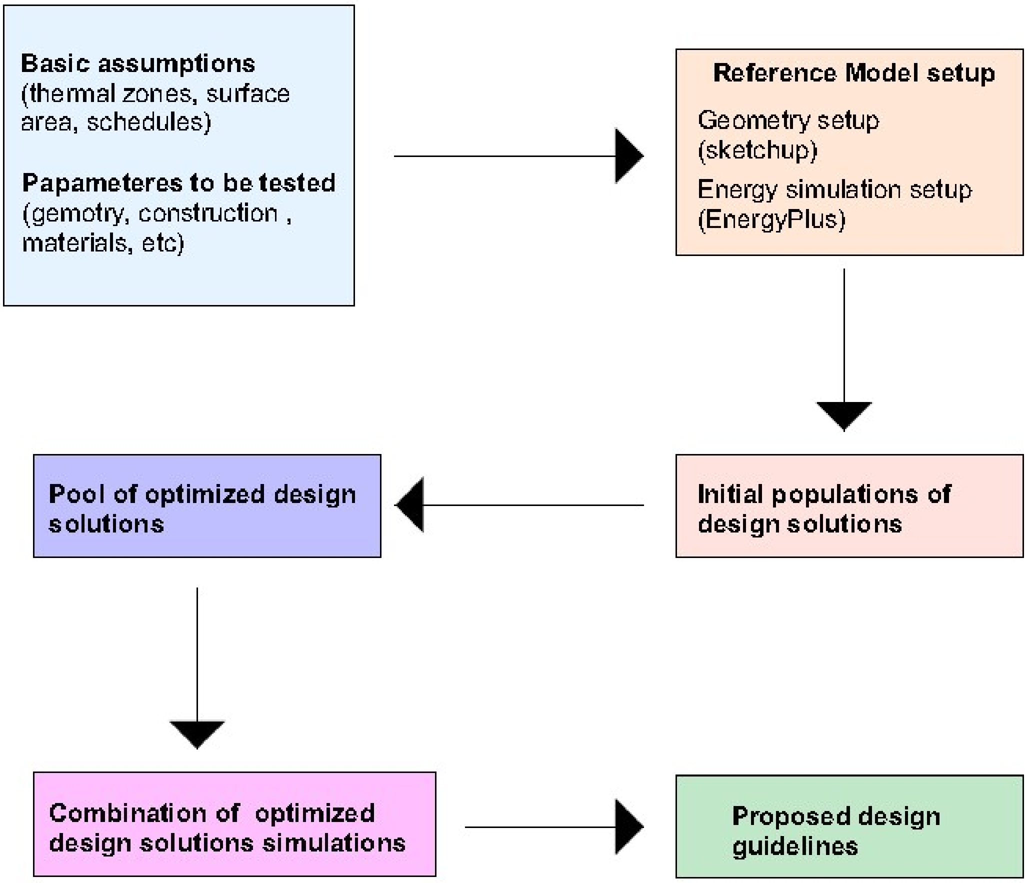


Figure 8. Flow chart of the proposed methodology

3.1 Basic assumptions

The reference model is a single story apartment, part of a residential block of flats. The block of flats or ‘’polykatoikia’’ is a typical kind of residential building, especially in big cities like Athens or Thessaloniki. The reason that the apartment was selected as a reference model was the intention to be representative of the existing situation of the existing building block and for the design optimization tools produced by the simulation to have a realistic implantation on it.

The model consists of two thermal zones. The apartment and the sunspace. The apartment is considered as a conditioned space, while the sunspace (in all simulations) is considered to be unconditioned. All the internal partitions of the apartment zone are neglected. In all simulations, the area and the thermal characteristics of the apartments are the same in order not to alter the energy simulation for any different parameter of the sunspace tested.

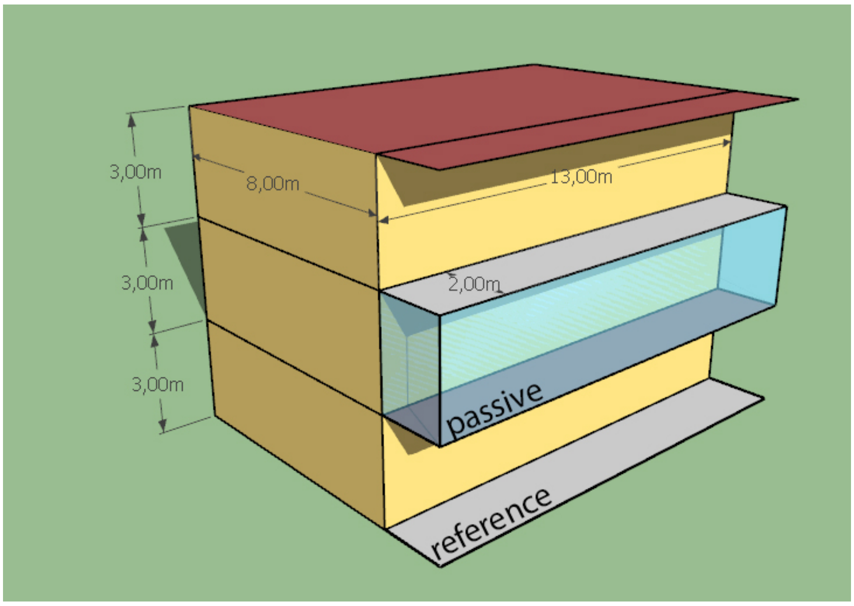


Figure 9. Reference model and passive solar sunspace mode representation (SketchUp screenshot)

Since the apartment that is simulated is considered to be a part of a larger multi-story residential building, all the walls have as an outside boundary the outdoor environment. In the contrary the ceiling and the floor slabs are assigned as surface boundary to each other. It is a safe assumption that all the apartments retain the same indoor conditions, they have the same internal gains and the same heat and infiltration losses.

3.2 2.2 Software used

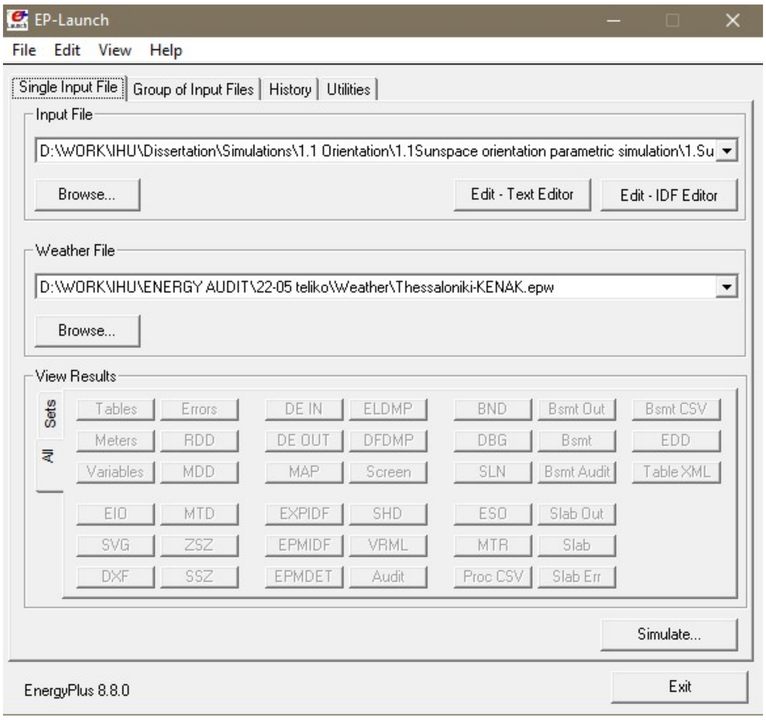
Energy plus

In order to produce an accurate calculation of the energy needs of a building it is necessary to perform a dynamic simulation. Dynamic simulation methods require computer support, since the procedure requires precision and time. For the cause of this paper, the software that was selected is the EnergyPlus.

EnergyPlus is a free open source software that was developed under funding from the U.S Department of Energy. The program, using a collection of systems and energy sources simulates the building and the energy systems connected to it, by taking into account different environmental and operating conditions given by the operator. The energy simulation follows the fundamentals of the heat balance principles.

Energy plus is used by a variety of engineers, architects and researches to module the energy requirements for heating cooling ventilation and lighting of a building. The software can be considered as a parametric analysis tool, since it allows the exploration throughout a range of variables (such as the materiality of the wall or the thermal characteristics of the glazing) in order to achieve optimization of design.

The main operation principle of the EnergyPlus software is that almost every information required for the energy simulation is specified in the input file. That means that in most cases no external data is necessary to be referenced since all the detail is already contained in the program. This approach does make the file include a lot of specification that may not be always a necessity. Consequently, there are some preliminary steps that need to be followed and some information to be gathered before starting to construct the input file in order to make sure that the model is operable.



Input File: D:\WORK\IHU\Dissertation\Simulations\1.1 Orientation\1.1Sunspace orientation parametric simulation\1.Su

Weather File: D:\WORK\IHU\ENERGY AUDIT\22-05 teliko\Weather\Thessaloniki-KENAK.epw

Figure 10. EnergyPlus launch interface

The simulation procedure, that the software uses, has as a central point a building model that is subjected to different external influences and usage schedules. All the data required about the location and the climatic condition required for the calculation process are contained in a weather file provided by the software official website. The input data contains the air temperature, the humidity levels, the diffuse and direct solar radiation, the cloudiness, the direction and the speed of air, the altitude and longitude of the selected area, the time zone as well as the calculation of the sun's position throughout every day of the year. (Petrović, 2019)

Sketchup

SketchUp is a 3D model computer program for a wide range of drawing applications such as the architectural modeling. SketchUp was developed by startup company @Last Software of Boulder, Colorado, co-founded in 1999 by Brad Schell and Joe Esch. Google acquired @Last Software on March 14, 2006 and then Trimble Navigation acquired SketchUp from Google on June 1, 2012.

The version used for the modeling is the Sketchup Make, introduced in May 2013 and is a free-of-charge version for home, personal and educational use.

3.3 2.3 Geometry and materials

The model consists of two zones. The apartment zone and the sunspace zone. Since the sunspace is considered as an unconditioned space the apartments zone is the one that will help us compare the energy efficiency of the different configurations tested.

The apartment has the size of a typical family house. It occupies an area of 104,00 s.m, its width is 8,00 m and its length is 13,00m while the height is 3,00 m, including both the floor and the roof slab. The geometry of the apartment remains the same during the whole procedure of the energy simulations.

Each one of the structural element of the model is characterized by a construction type. The construction layers are defined in the .idf model in the energy plus software, starting from the outside layer to the inside one. The following construction are assigned.

1) External wall: The exterior wall construction is assigned to all the walls of the apartment in contact with the exterior. The layers are plaster, 10 cm of expanded polystyrene used as thermal insulation, 24 cm of clay brick and plaster.

	External walls			
	thickness	thermal conductivity	thermal resistance	
Material layer	d m	λ W/mk	d/λ m^2K/W	
1) Plaster.Asv	0,020	0,870	0,023	
2)Clay brick	0,240	0,580	0,414	
3)Extruded polystyrene	0,100	0,035	2,857	
4) Plaster.Asv	0,020	0,870	0,023	
	0,380			
		U value	0,301	m^2K/W

Table 1. Material properties of external wall construction

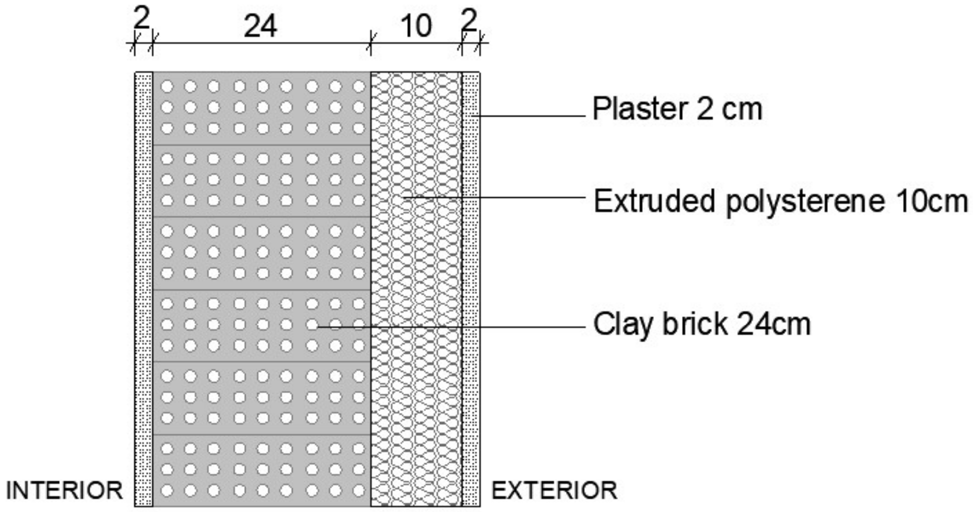


Figure 11. Exterior wall construction

2)Flat roof no ins: Non-insulated concrete slab that consists of a layer of ceramic tiles, a layer of mortar, a layer of non-reinforced cement, the cement layer and the plaster layer.

Flat roof_no insulation, Floor_no insulation				
	thickness	thermal conductivity	thermal resistance	
	d	λ	d/λ	
Material layer	m	W/mk	m^{2}K/W	
1 Plaster.Asv	0,020	0,870	0,023	
2)Reinforced concrete	0,200	2,500	0,080	
3)Non reinforced concrete	0,040	0,810	0,049	
4)Mortar	0,010	1,400	0,007	
5)Ceramic tiles	0,015	1,840	0,008	
	0,285			
		U value	6,269	m^{2}K/W

Table 2. Material properties of non-insulated roof and floor slab.

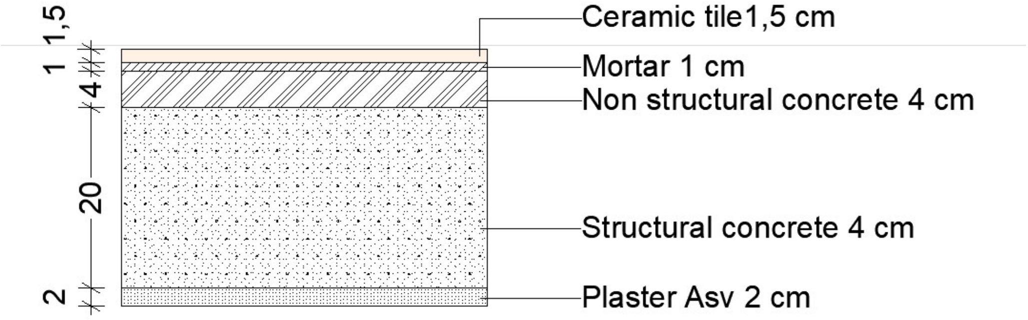


Figure 12. Non insulated slab construction

3)Thermal mass walls: The walls that act as an internal boundary between the apartment and the sunspace area. The thermal characteristics of these walls have a very high contribution to the general energy performance of the sunspace in general. In the reference model the thermal mass wall consist of a 24cm thick layer of clay brick between two layers of plaster. The wall is uninsulated.

Thermal mass walls

	thickness	thermal conductivity	thermal resistance	
Material layer	d m	λ W/mk	d/λ m^{2}K/W	
1) Plaster.Asv	0,020	0,870	0,023	
2)Clay brick	0,240	0,580	0,414	
4) Plaster.Asv	0,020	0,870	0,023	
	0,280			
		U value	2,175	m^{2}K/W

Table 3. Material properties of thermal mass wall

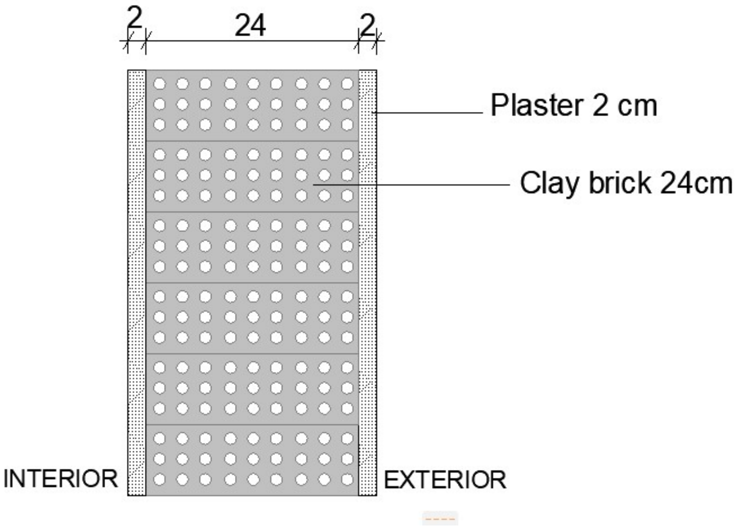


Figure 13. Thermal mass wall construction (reference model)

3)Sunspace glazing: The glazing of the sunspace in the reference model consists only of a single layer of clear glass 4mm thick.

Sunspace glazing (reference model)				
	thickness	thermal conductivity	thermal resistance	
Material layer	d m	λ W/mk	d/λ m^2K/W	
1) Clear Glass	0,004	1,100	0,004	
		U value	275,000	m^2K/W

Table 4. Material properties of sunspace glazing construction (reference model)

3.4 Schedules/Internal gains

In order for the energy plus program to simulate accurately the energy performance of the apartment we need to provide more information. The thermostat adjustments, the occupation of the area, the infiltration and ventilation losses, the internal heat gains by the electrical equipment and the lights are some parameters that can drastically alter the result of the simulation. The heating and cooling system are ideal air systems so no losses or energy conversion coefficients are taken into account.

Since the scope of the study is to investigate only the contribution of the sunspace to the energy behavior of the apartment all the schedules are set to equal values for all the simulations.

Heating schedule

The heating schedule is the thermostat settings throughout the year. The heating period is defined from the 01/01 to 30/4 and from 01/10 to 31/12 of each year. For these periods of the year and for all days the thermostat settings are:

From 0:00 Until 8:00 16ºC

From 8:00 Until 22:00 20ºC

From 22:00 Until0:00 16ºC

That schedule means that the heating system goes on if the temperature inside the zone drops below 16º and goes off when it surpasses 20ºC.

During the cooling period the temperature of the thermostat is set for all days and through the day at 0ºC. That means that we neglect the heating needs during this period, if any.

Cooling schedule

The cooling period is defined from 01/05 to 30/09 of each year. During this period of the year the thermostat settings are:

From 0:00 Until 10:00 100ºC

From 10:00 Until 24:00 26ºC

That means that the cooling systems goes on only after 10:00 and when the inside temperature rises above 26ºC

During the heating period the thermostat is set at 100ºC, so the cooling needs are neglected.

People/ Occupancy schedule

The Occupancy schedule defines the number of habitats that are present in the house during the day. This schedule is used to calculate different parameter like the internal hat gains by people, the ventilation flow rate etc. According to KENAK 20m^2 correspond to one habitat. Since the apartment is approximately 100m^2 the occupants are 5. The schedule settings are the following:

from the 01/01 to 30/6
From 0:00 Until 08:00 5 persons
From 08:00 Until 18:00 2 persons
From 18:00 Until 24:00 5 persons

from the 01/07 to 31/8
From 0:00 Until 08:00 2 persons
From 08:00 Until 18:00 1 persons
From 18:00 Until 24:00 2 persons

from the 01/09 to 31/12
From 0:00 Until 08:00 5 persons
From 08:00 Until 18:00 2 persons
From 18:00 Until 24:00 5 persons

Lighting schedule

The lighting schedule is used for simulation the internal gains of the lights. The values of the lighting schedule are fractions ranging from 0 to 1. These fraction represent the portion of the lights that operating during different periods throughout the day. The schedule settings are:

From 0:00 Until 08:00 value=0
From 08:00 Until 17:00 value=0,3

From 17:00 Until 24:00 value=0,75

The schedule tries to simulate the use of artificial lighting of a family throughout the day. The Watts per zone floor area us given at 6,4W/m^2.

Equipment schedule

All the electrical appliances of the house work throughout the day. So the schedule assigned is the always on for the whole year. The design level calculation method is the Watts/Area. The value is set at 2 Watt/m^2.

Zone Infiltration: Design Flow rate.

The design flow rate calculation method chosen is the air changes per hour for both the apartment and the sunspace zone. For the apartment zone the value is set at 0,8 air changes per hour on an always on schedule.

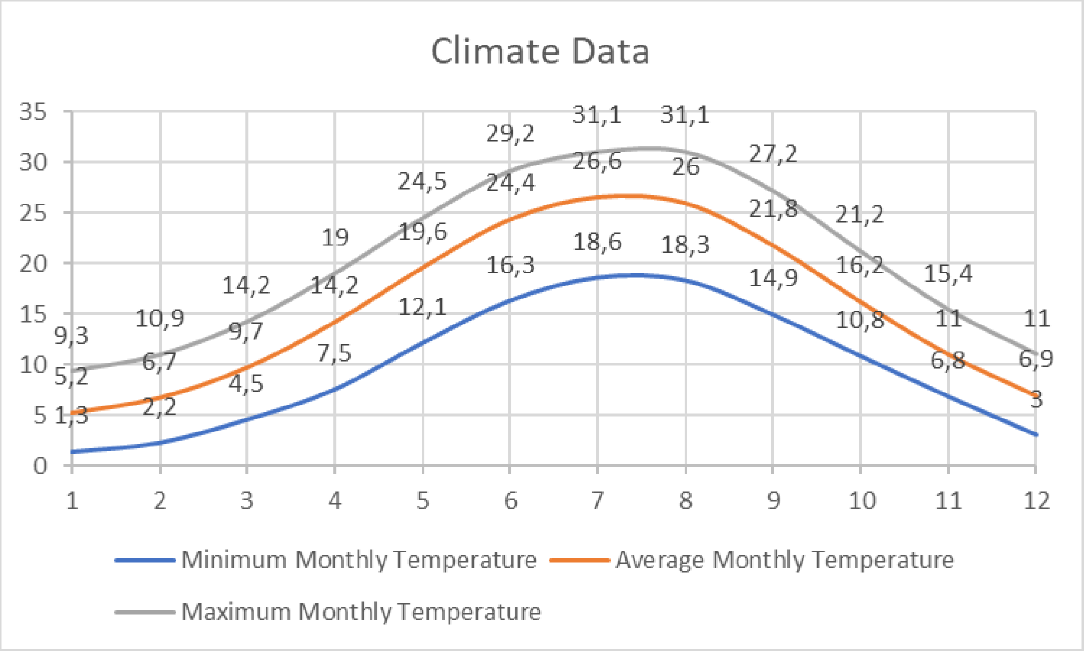
For the sunspace zone the air changes per hour value is set at 1 following the Sunspace infiltration schedule. This schedule takes into account that during the cooling period the glazing of the sunspace is wide open throughout the day in order to minimize the heat gains. So from the 01/01 to 30/4 the value is set to 1, from the 01/05 to 30/09 is set to 100 and from 01/10 to 31/12 is set to 1.

Ventilation schedule

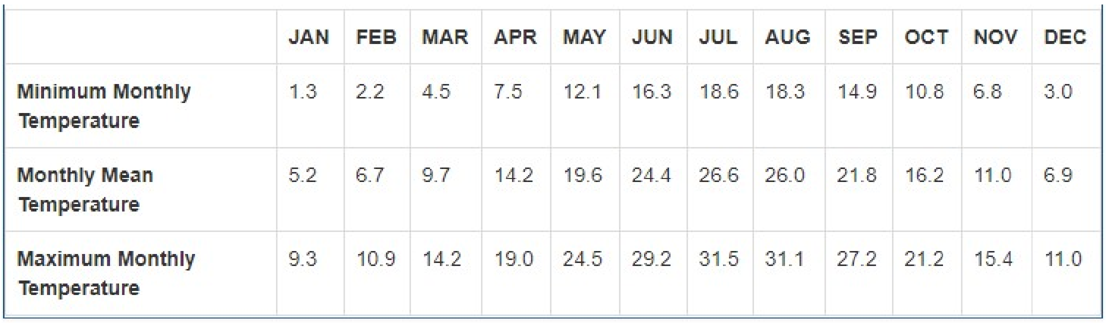
The ventilation refers only to the apartment zone since the sunspace is considered to be a non-conditioned space. The flow rate is set at 0,0075 m3/s-person and follows the Occupancy schedule.

3.5 Location/ Climatic conditions

The climate of the Thessaloniki region can be considered as Mediterranean, with a pronounced continental influence over the different seasons. The temperature reaches the highest level in July and the lowest in January. During the cold period, very cold air masses appear, often freezing rivers and lakes, even Thermaikos near the coast. Typical are also the mild and sunny days observed around mid-winter, the relatively large number of summer and tropical days and the decrease in rainfall during the summer. The average annual air temperature is around 16 °C. the minimum monthly temperature (January) around 1.3 ° C and the highest (July) 31.5 ° C. The absolute maximum has reached 42 ° C and the absolute minimum is -10 ° C. (Graph 1 & Table 5).



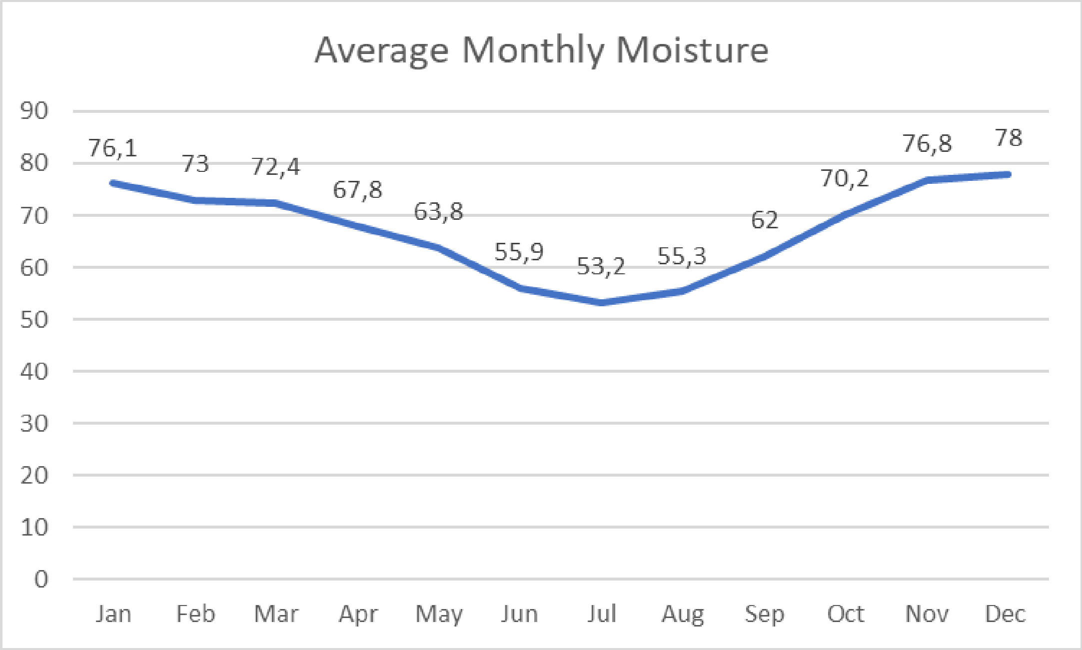
Graph 1 Average, minimum, maximum monthly temperature



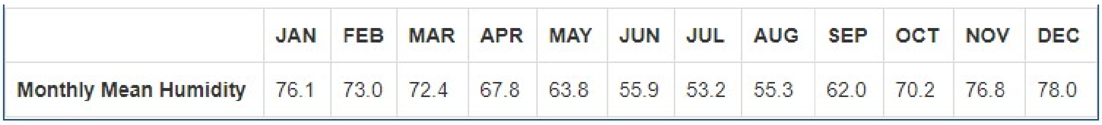
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Minimum Monthly Temperature	1.3	2.2	4.5	7.5	12.1	16.3	18.6	18.3	14.9	10.8	6.8	3.0
Monthly Mean Temperature	5.2	6.7	9.7	14.2	19.6	24.4	26.6	26.0	21.8	16.2	11.0	6.9
Maximum Monthly Temperature	9.3	10.9	14.2	19.0	24.5	29.2	31.5	31.1	27.2	21.2	15.4	11.0

Table 5. Average, minimum, maximum monthly temperature of Thessaloniki

Over a year, about 140 days have a maximum temperature of above 25 ° C and about 70 above 30 ° C.



Graph 2. Average Monthly Moisture of Thessaloniki



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Monthly Mean Humidity	76.1	73.0	72.4	67.8	63.8	55.9	53.2	55.3	62.0	70.2	76.8	78.0

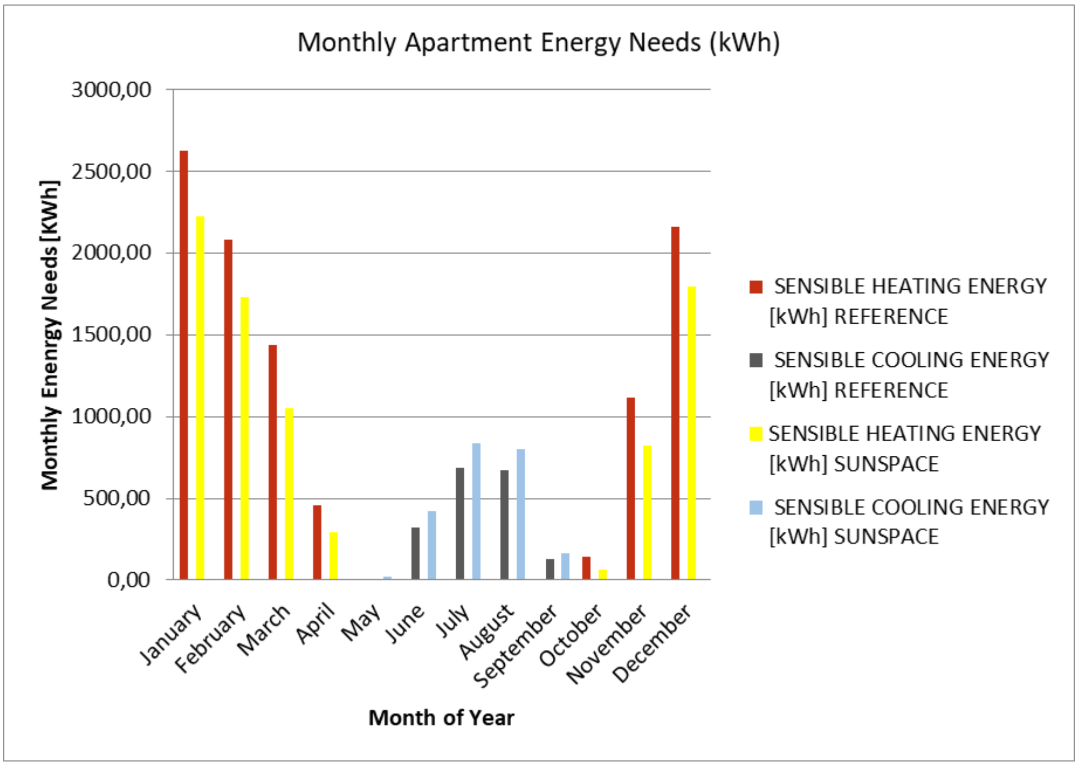
Table 6. Average monthly Moisture

The levels of humidity in the area of Thessaloniki are usually high (we can see from the graph that the average monthly moisture ranges between 53.2% in July and 78% in December) due to the fact that Thessaloniki is a coastal city (Graph 2 & Table 6). As a result, the actual living conditions become harsher both in winter and summer than one could deduce by taking into account the average temperatures.

4 Energy performance simulation and analysis

This paper tries to present the outcome of a research aiming to provide information about the energy behavior of the passive solar sunspace. According to the general strategy a series of parametric simulation will be held, starting from preliminary to more complex and multidisciplinary one, measure the impact of various interventions tested.

Initially, every parameter will be tested individually running the respective energy simulations. Subsequently, according to the results produced, they will be examined in combinations, two or parameters at the time, in order to determine their interdependence. The first step towards the optimization of the sunspace parameter is to examine the influence of the sunspace into the energy performance of the apartment. In this first base scenario simulation the outcome that interest is the annual and monthly energy needs. The following Graph 3 that depicts the apartment's monthly energy needs for heating and cooling shows that the application of the sunspace can help reduce the energy needed.



Graph 3. Effect of passive solar sunspace to monthly apartment energy needs

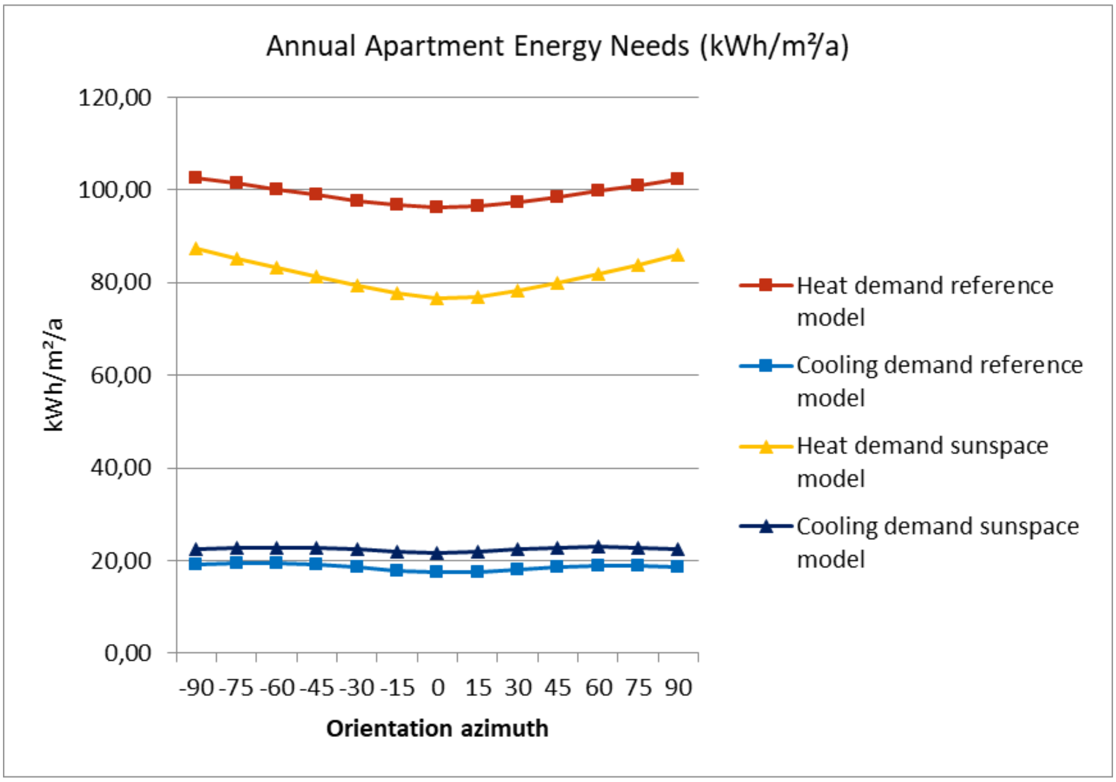
4.1 Sunspace orientation parametric energy simulation

An important parameter that can be decisive for the amount of solar radiation the building will get, and as a result the heat gains, is the sunspace orientation. There are some conclusions that the scientist has been driven into concerning the optimal orientation. South orientated sunspaces are proven to be ideal since a south facade can accept the biggest amount of solar radiation throughout the year. Northern facades receive the lowest amount of radiation, most of it during summer, while the eastern and western facade may accept more solar radiation during summer time and less during winter compared to the southern one. There is an empirical rule that a small deviation, no more than 20° does not substantially affect the energy performance of a sunspace.

Although, it is crucial to perform a series of simulation in order to quantify the magnitude of the effect of the orientation to the energy performance of the sunspace, that corresponds to the location and the geometry of the reference model chosen.

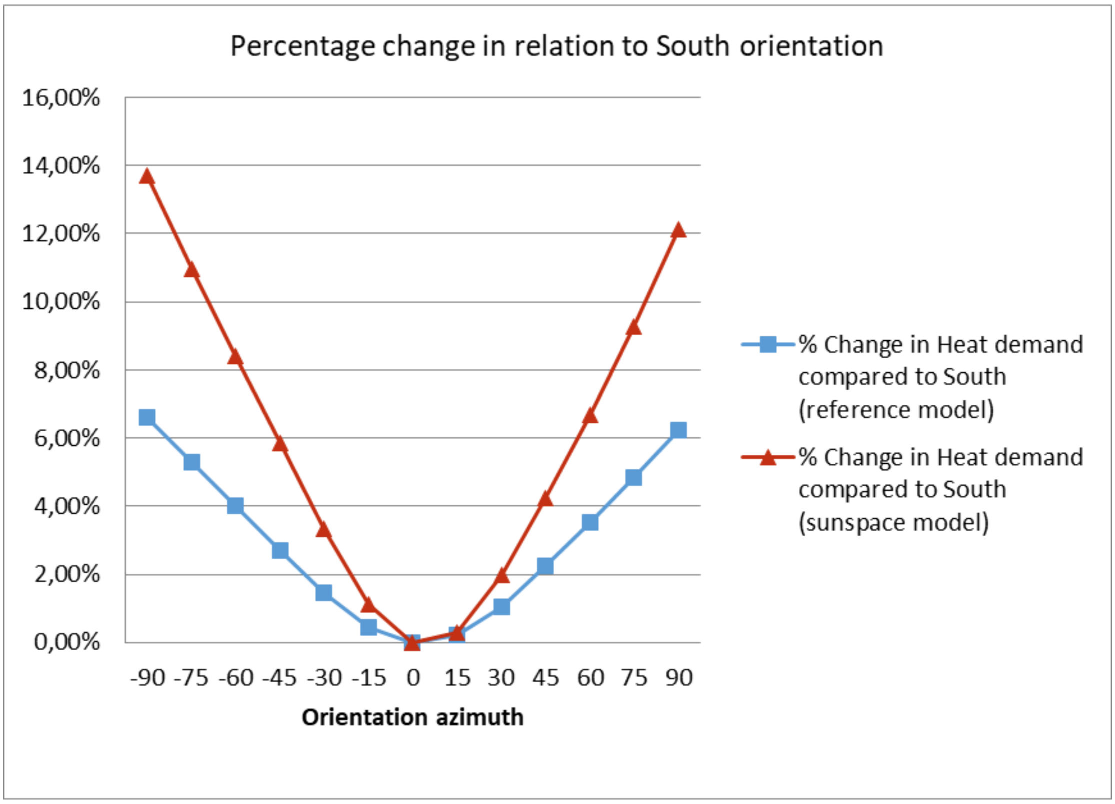
Consequently, the first series of the sunspace energy behavior analysis will examine the effect of the orientation to the apartment's energy needs. In the building section of the energy plus, there is a value name North axis in degree units that defines the orientation of the house. Instead of a numerical value the field was given the value $North, which correspond to a deviation from south orientation between -90° to 90° with a step of 15°. That means that the simulation will run 13 times, with the only parameter changing to be the orientation.

The series of simulation ran for two different models. The first one was reference model, which has no sunspace attached to it and the second model which consists of two thermal zones the apartment(reference) and an attached sunspace at its long side. The scope of this first series of simulation was not only to investigate the effectiveness of the sunspace in relation to orientation but also to compare the energy performance of an apartment has a passive solar thermal system attached to it with one that does not.

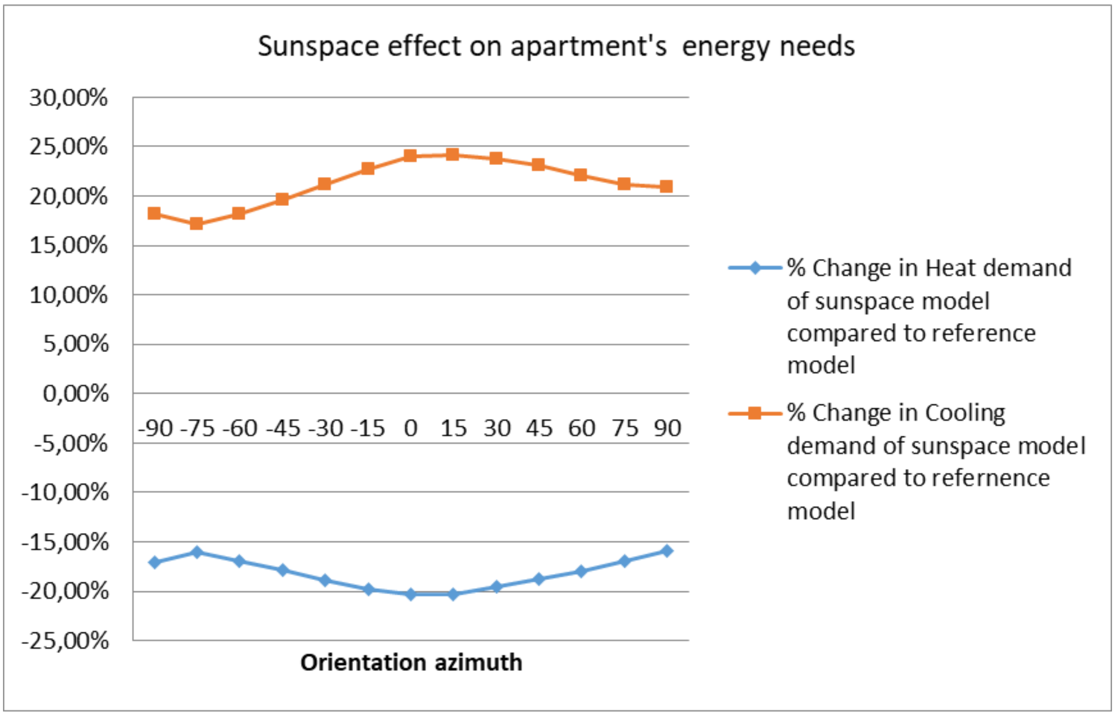


Graph 4. Effect of orientation to the annual apartment energy needs

Graph 4 displays the annual apartment energy needs for cooling and heating, expressed in KWh/m^2, in relation to the orientation azimuth. As expected the optimal orientation is the Southern, but as the graph depicts a slight deviation up to 15° degrees have no significant effect. In regard of the heating needs the application of a sunspace can lead to a reduction about 20 KWh/m^2, without any optimization concerning the geometry to the material used. In the contrary the cooling needs seem to increase slightly due to the overheating, since no shading device was applied for the current simulation.

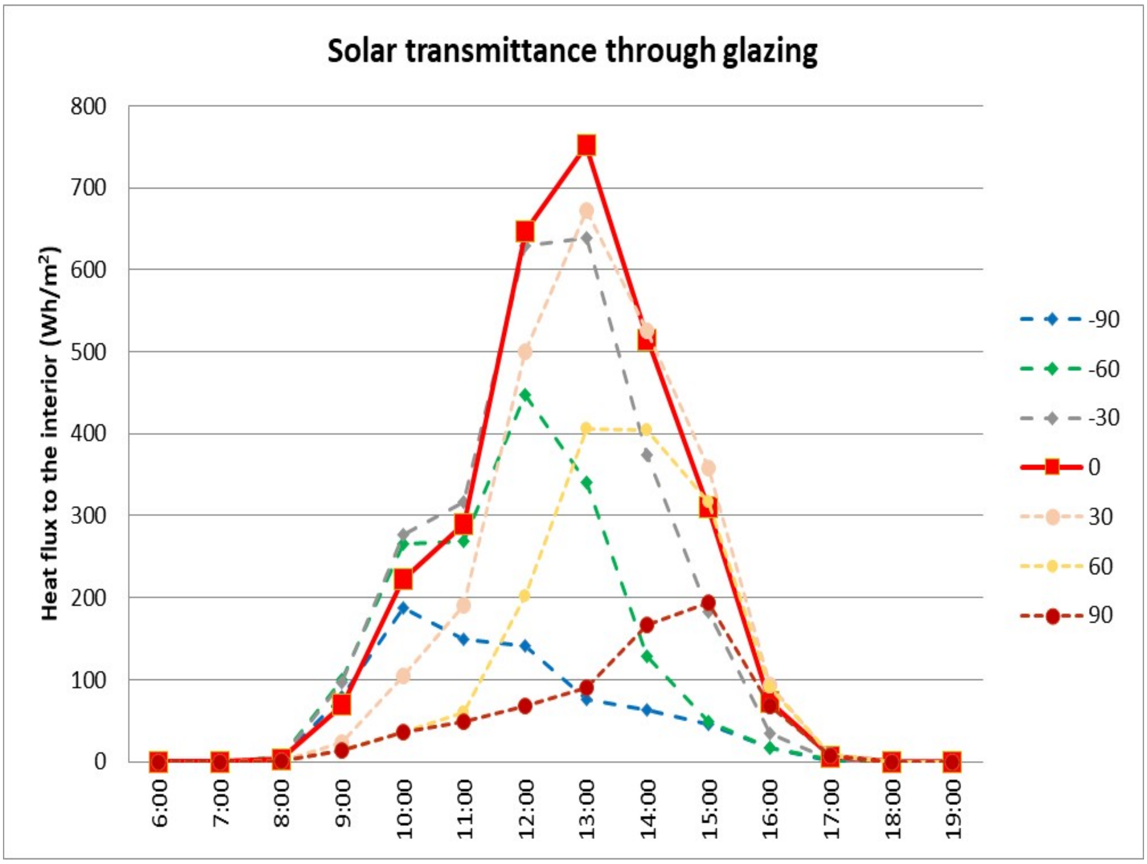


Graph 5. Percentage change in annual Energy needs in comparison to the South orientation.



Graph 6. Sunspace effect on apartment's energy needs

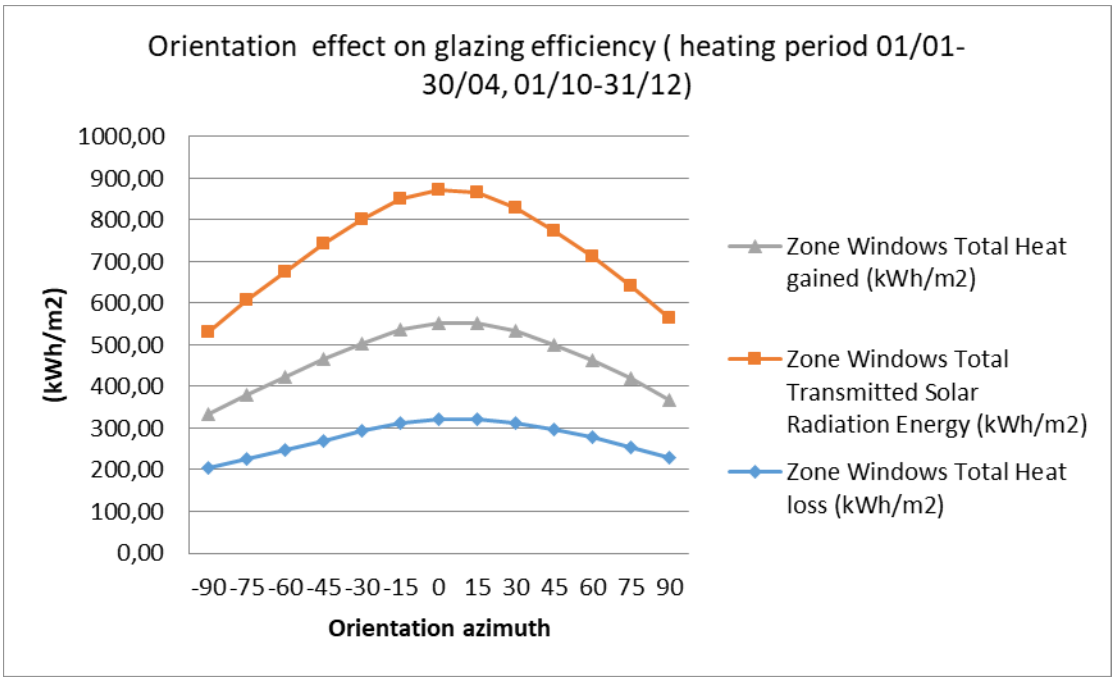
Graph 5 displays the percentage change in heating demand of the apartment for every orientation azimuth in comparison to the heat demand of the southern orientation. The graph looks almost symmetrical having as a central axis the 0 degree deviation from South. An important observation is that the percentage difference between eastern and western orientation compared to south when the sunspace is applied (11%-12%), is higher than the reference model (6%). This is due to the more efficient use of the solar potential by the sunspace. Furthermore, the western orientation seems to work better for the sunspace model. For example, by comparing the heating demands between the -45o and 45o orientation azimuth we can notice and almost 2% difference.



Graph 7. Hourly solar transmittance through the sunspace glazing (Wh/m^2)

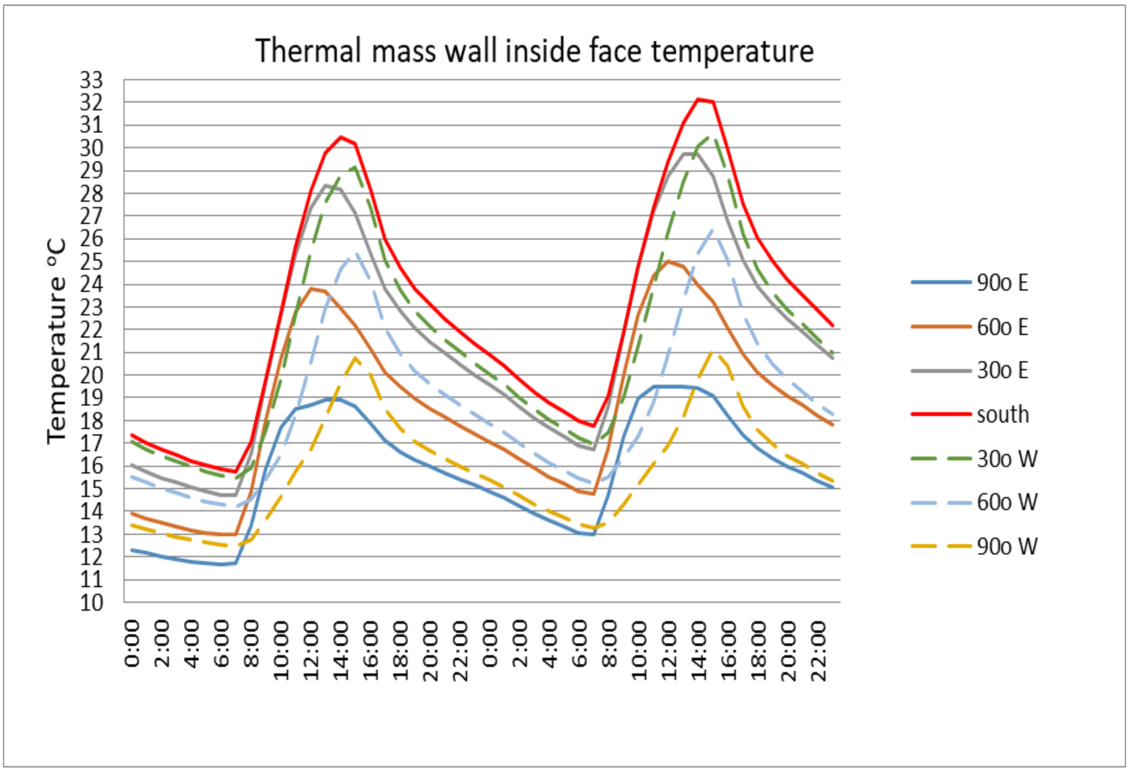
An important parameter regarding the effectiveness of the sunspace in reducing the energy needs of the apartment, is the amount of solar radiation that enters the sunspace throughout a heating period’s day. Graph 7 shows the solar radiation transmitted to the interior of the sunspace during the chosen date (19/12) in an hourly basis. The glazing facade orientated towards the East receives the peak radiation in the morning, while the one facing the West during evening. As anticipated the south orientated glazing surface receives the highest amount of solar radiation per area around midday.

In total, during the heating period (01/01-30/04 & 01/10-31/12) the solar radiation that is transmitted through the glazing in a South orientated sunspace is almost 350kWh/m^2 of glazing area higher than a sunspace orientated towards the east or the West. Although, since not all the transmitted radiation is considered as heat gain, the actual raise of the heat gain is about 250kWh/m^2 of glazing area. Furthermore, a south orientated sunspace has higher heat losses comparing to other orientations. (Graph 8)

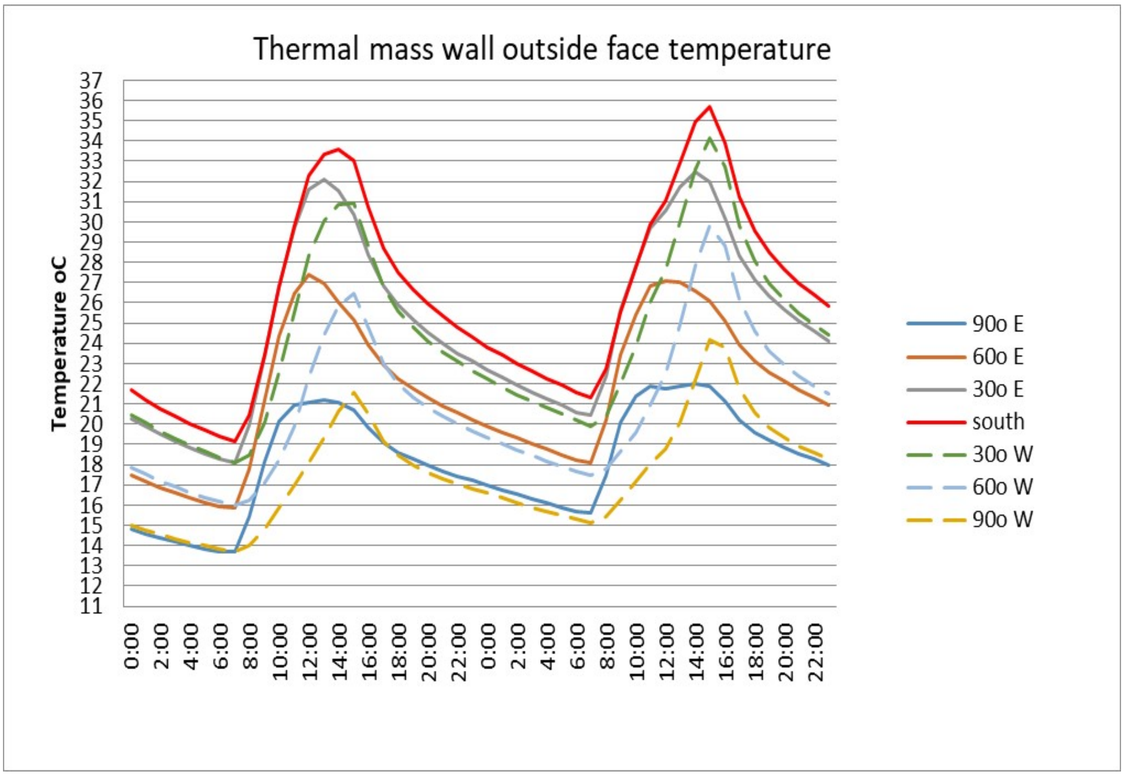


Graph 8. Orientation effect on glazing efficiency (heating period 01/01-30/04, 01/10-31/12) (KWh/m^2)

The peak hour of every orientation can affect the energy behavior of the thermal mass wall and consequently the indoor thermal condition of the apartment. Graphs 9 & 10 present the thermal mass wall inside and outside face temperature during two consecutive days (12/12-13/12). Similarly to the solar transmittance graph both the inside and outside surface temperature have different peaks through the day in accordance to the orientation. The South orientation is the optimal one, although the max temperature reached for the 30° East and 30° West orientation have no significant difference to the southern one.

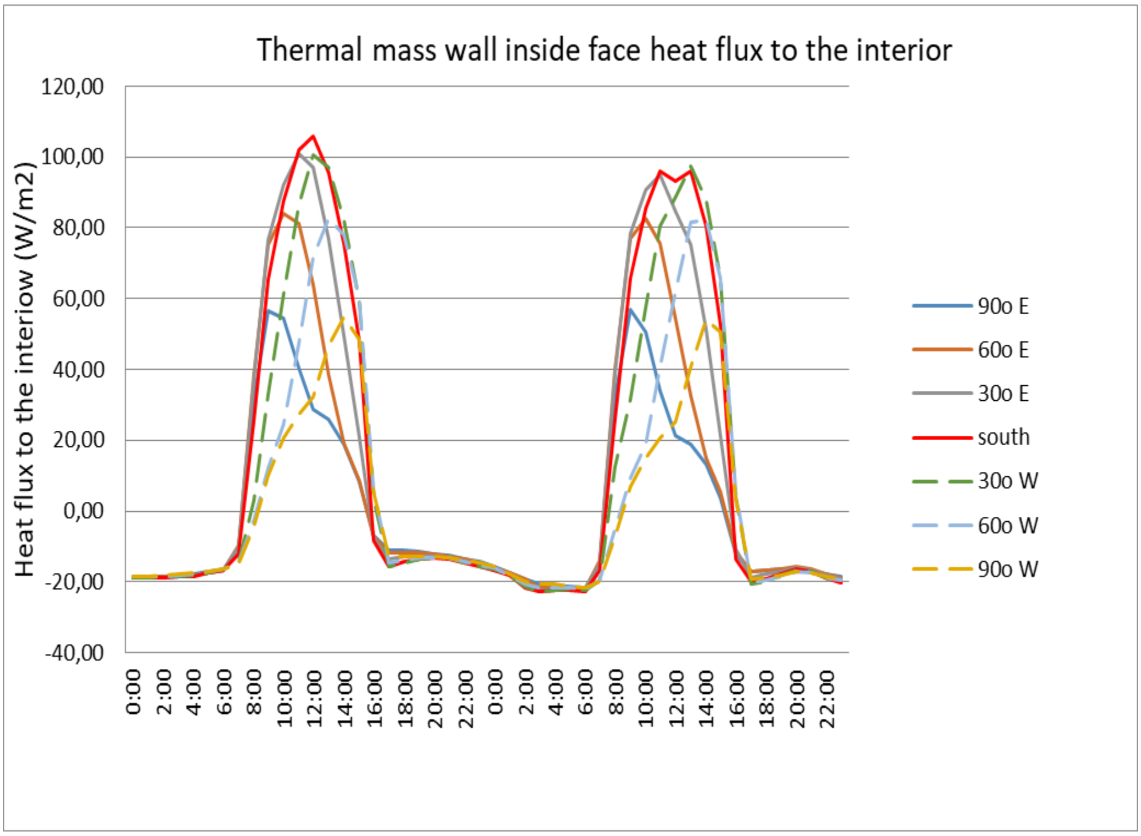


Graph 9. Thermal mass wall inside face temperature (°C)



Graph 10. Thermal mass wall outside face temperature (°C)

An interesting fact is that the outside face temperature of the thermal mass wall can reach up to 36ºC even during winter, mainly during midday to afternoon hours (around 15:00). On the other hand, the internal face of the wall reaches the max of 32 ºC during the same period of the day.



Graph 11. Thermal mass wall outside face temperature (oC)

The outside and inside temperature of the thermal mass wall can be interpreted in a different way as heat transfer between the adjoining apartment and the sunspace area. Graph 11 shows the hourly amount of heat flow of the inside face of the thermal mass wall. South orientation once more performs the best in terms of heat gain. The interesting fact is that when the solar radiation is absent the heat moves from the interior to the exterior, which is translated into heat losses. A solution that may be effective in reducing or eliminating this unwanted transfer of heat is the application of moveable insulation on the thermal wall, that will be studied later on.

4.2 Geometry and positioning of the sunspace in relation to the apartment parametric energy simulation

There are several types of sunspaces and their main classification parameter is the way that the sunlight is collected, accumulated and transferred among the rooms of the apartment. The type that the paper researches is the one with a thick thermal storage wall. Therefore, in all the configurations tested in this chapter, the sunspace consists of two or three glazing surfaces and at least on thermal mass wall in contact to the apartment. Six configurations will be examined in total, each one representing a different architectural application of the attached sunspace. The orientation of the sunspace for all simulations is towards South and o alterations have been made to the schedule or other parameter compared to the orientation simulations.

4.2.1 Configurations representation

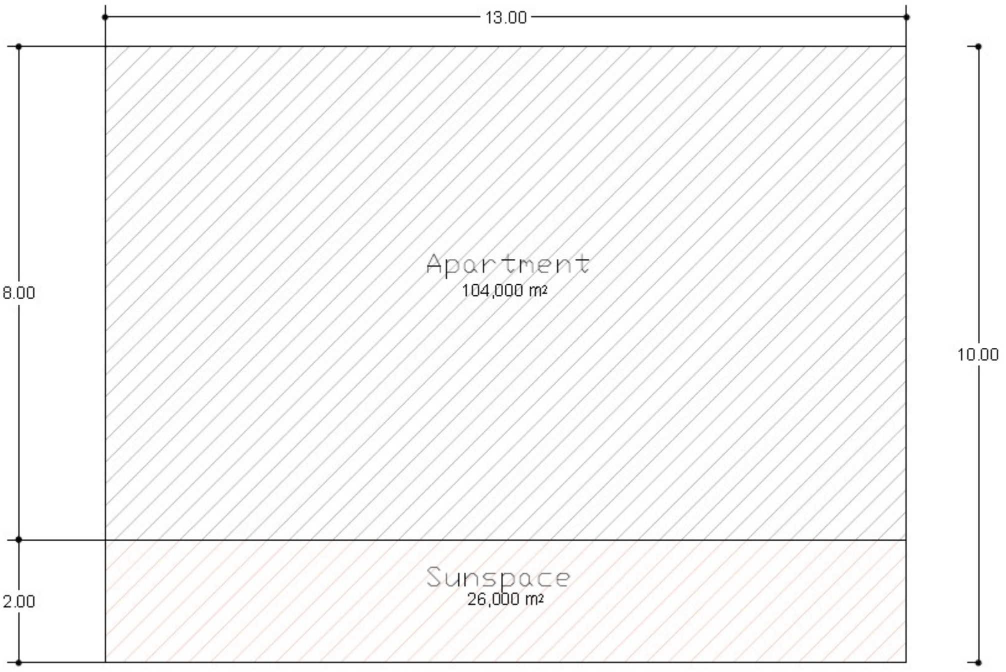


Figure 14. Configuration 1, Sunspace attached along southern facade

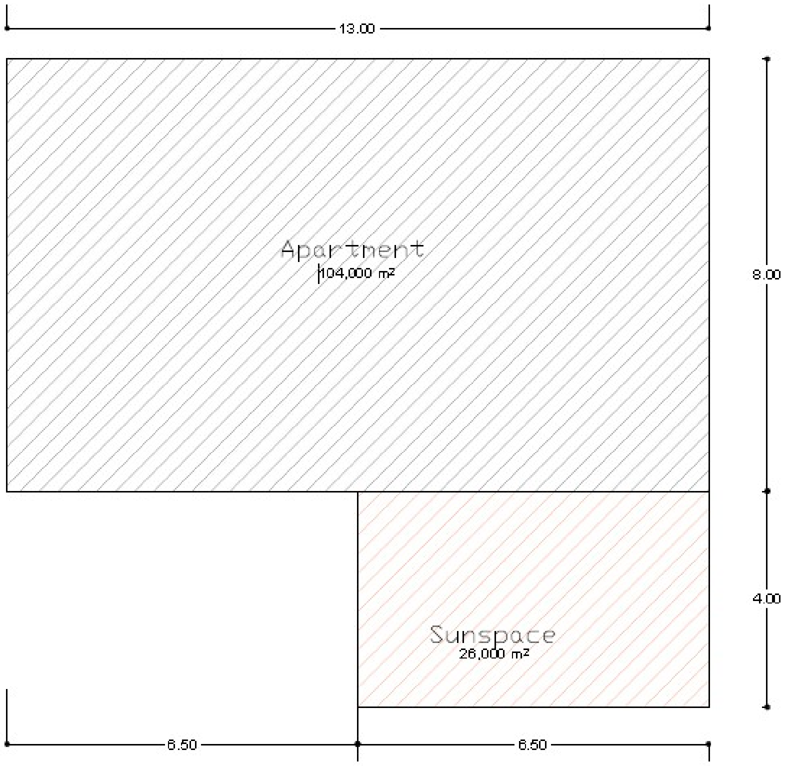


Figure 15. Configuration 2, Sunspace attached on the east half of the southern facade

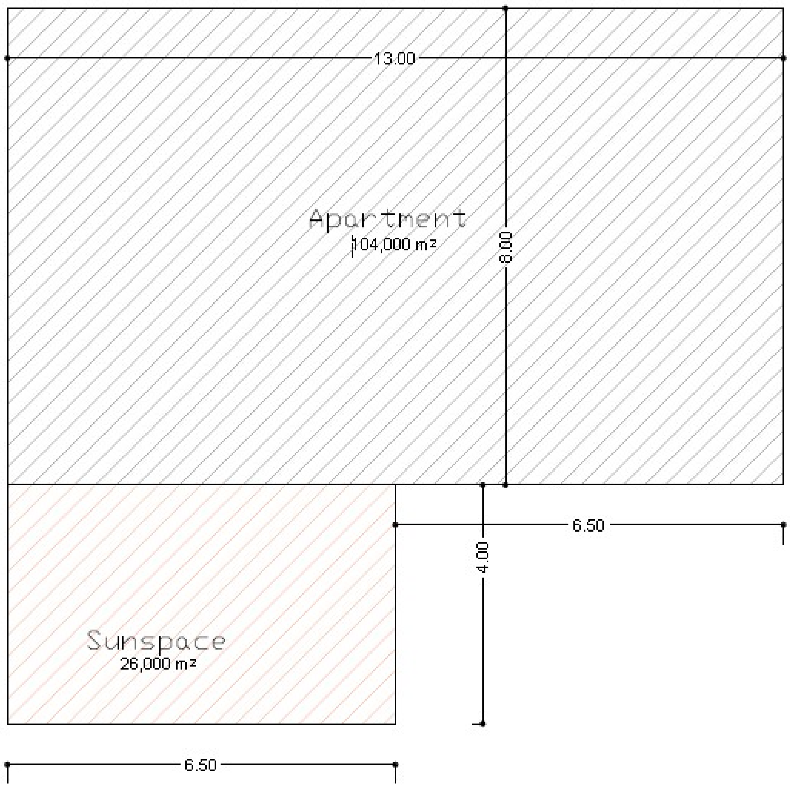


Figure 16. Configuration 3, Sunspace attached on the western half of the southern facade

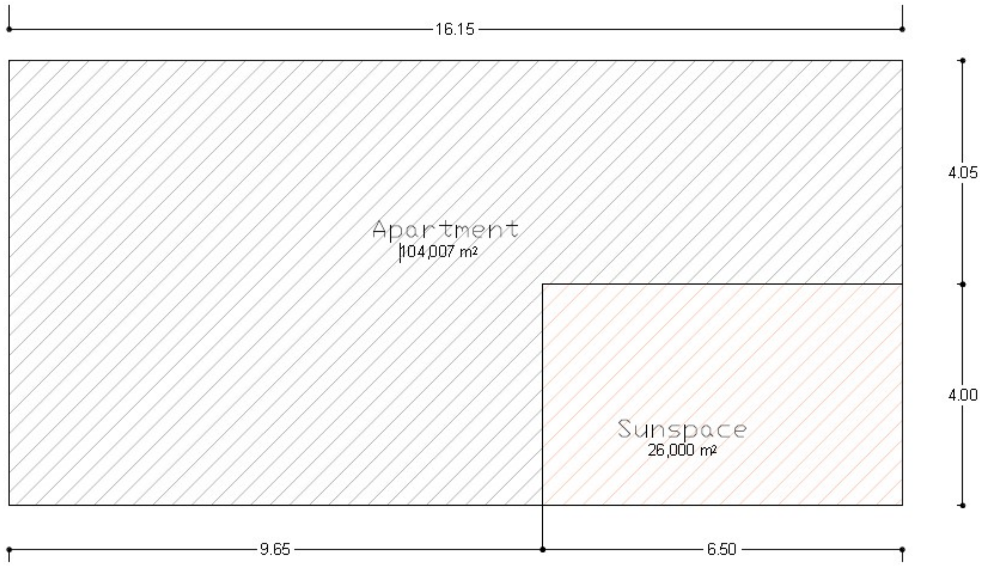


Figure 17. Configuration 4, Sunspace integrated at the southeastern corner of the apartment.

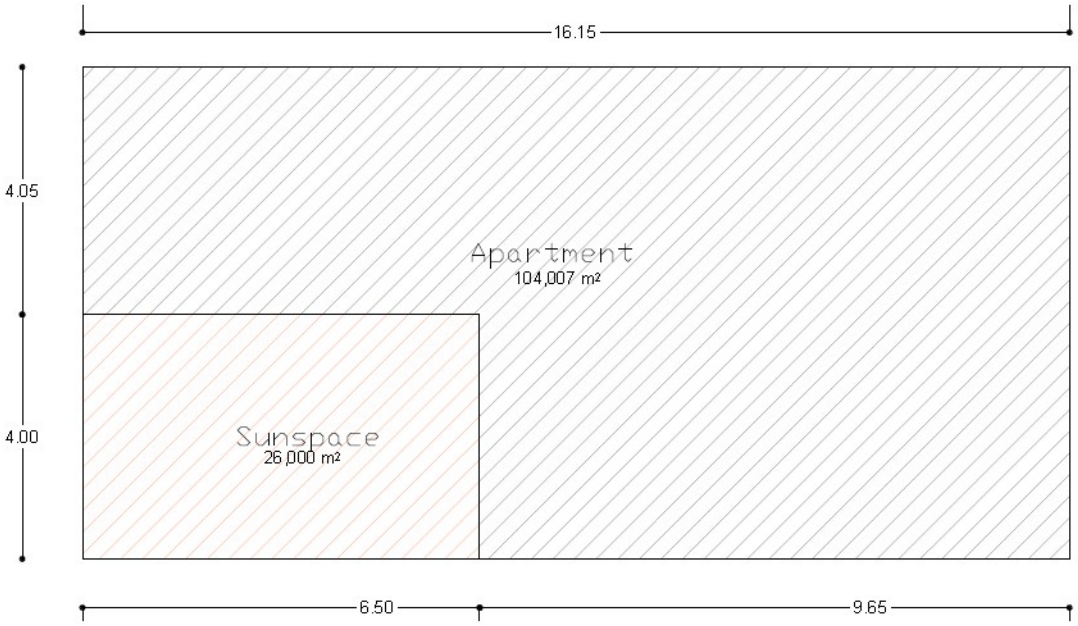


Figure 18. Configuration 5, Sunspace integrated at the southeastern corner of the apartment.

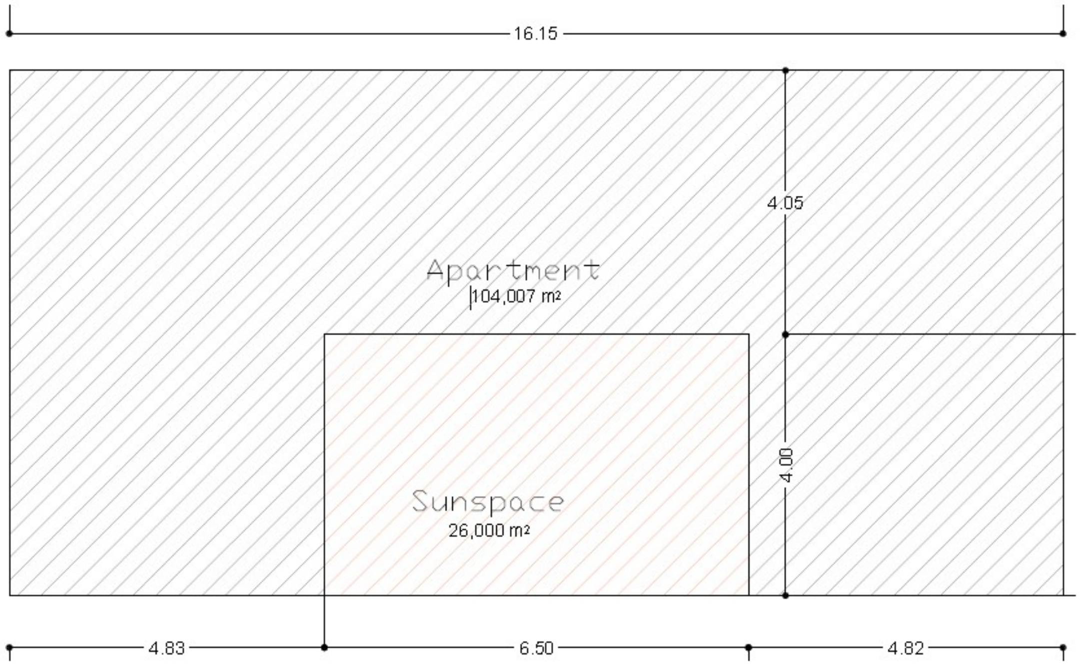


Figure 19. Configuration 6, Sunspace fully integrated in the middle of the southern facade.

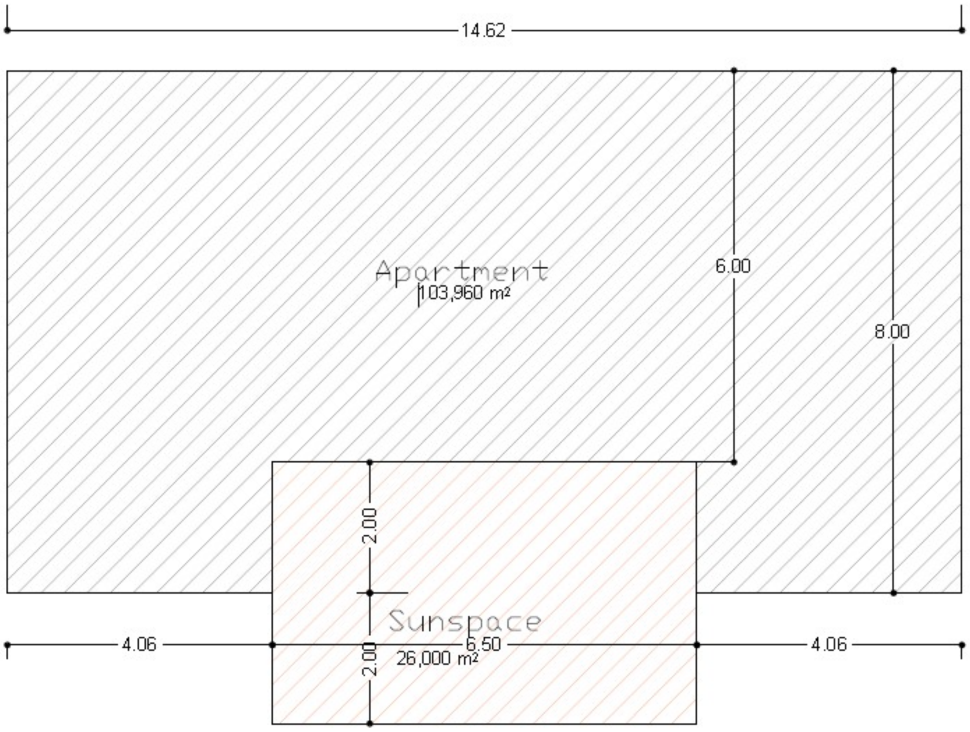
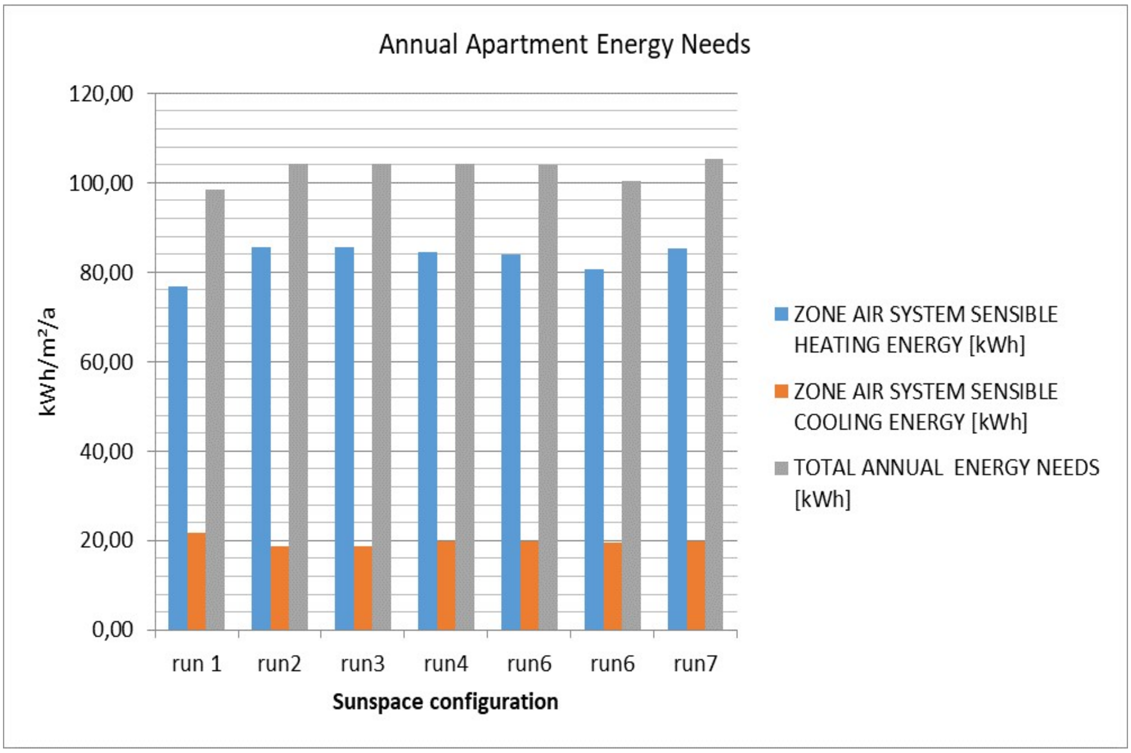


Figure 20. Configuration 7, Sunspace partially integrated in the middle of the southern facade.

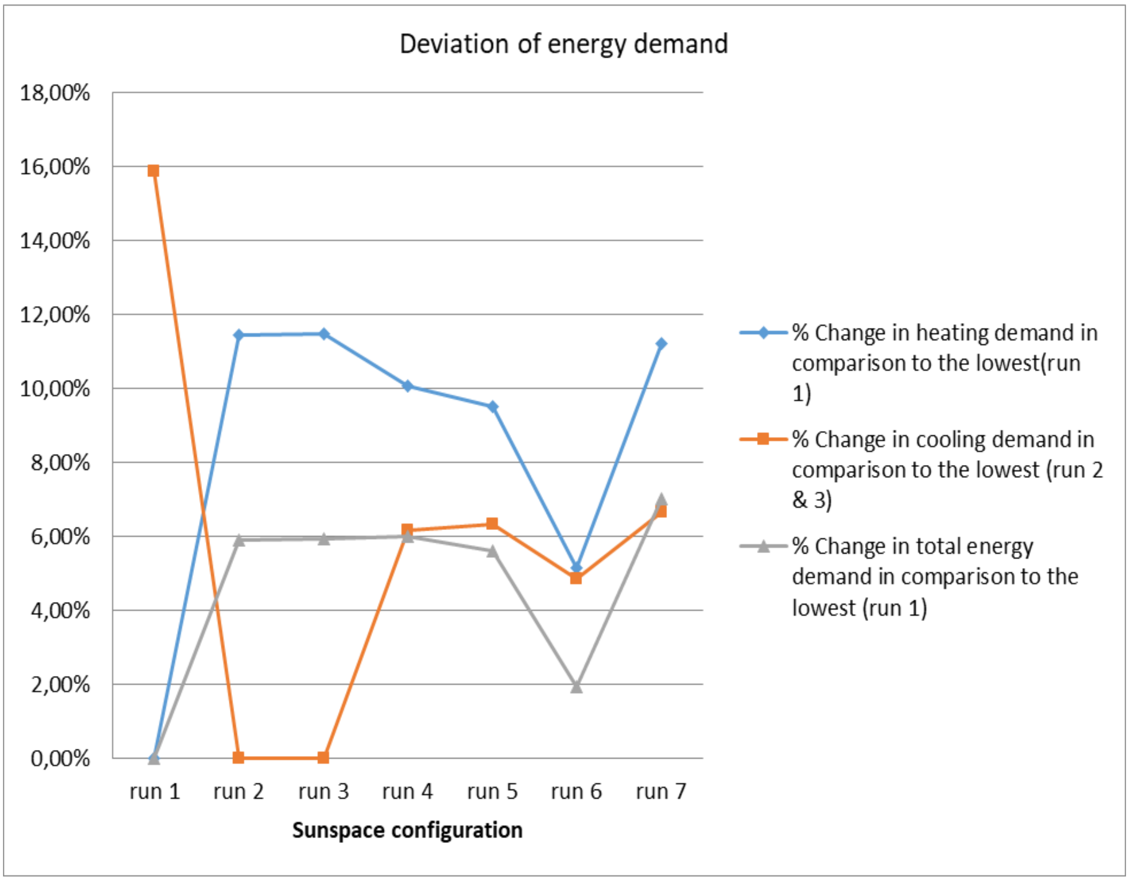
4.2.2 Simulations analysis

	Annual Apartment Energy Needs (kWh/m^2/a)			Geometry effect on apartment's energy needs		
	Heating demand	Cooling demand	Total energy demand	% Change in heating demand in comparison to the lowest(run 1)	% Change in cooling demand in comparison to the lowest (run 2 & 3)	% Change in total energy demand in comparison to the lowest (run 1)
run 1	76,73	21,66	98,39	0,00%	15,85%	0,00%
run 2	85,52	18,70	104,21	11,45%	0,00%	5,91%
run 3	85,53	18,70	104,23	11,46%	0,00%	5,93%
run 4	84,46	19,85	104,30	10,07%	6,16%	6,01%
run 5	84,03	19,88	103,90	9,51%	6,31%	5,60%
run 6	80,70	19,61	100,30	5,16%	4,87%	1,94%
run 7	85,35	19,94	105,29	11,23%	6,66%	7,01%

Table 7. Results of the sunspace geometry parametric energy simulation

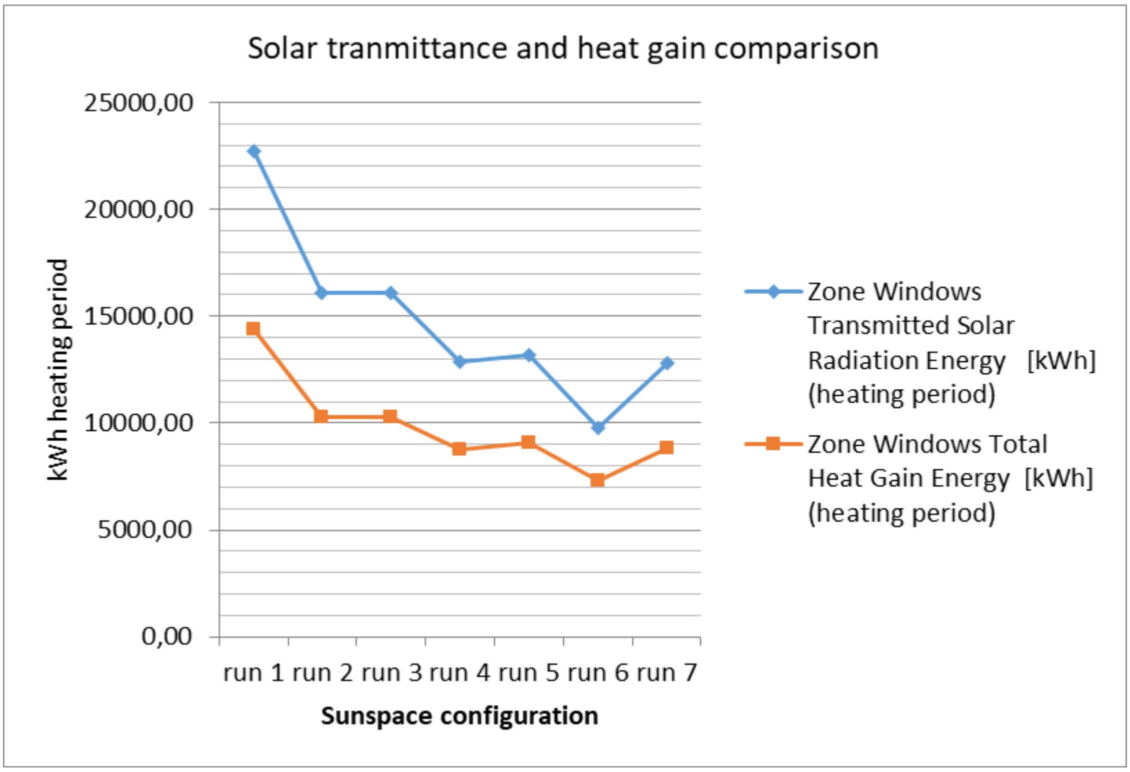


Graph 12. Annual apartment energy needs for the 7 selected configurations

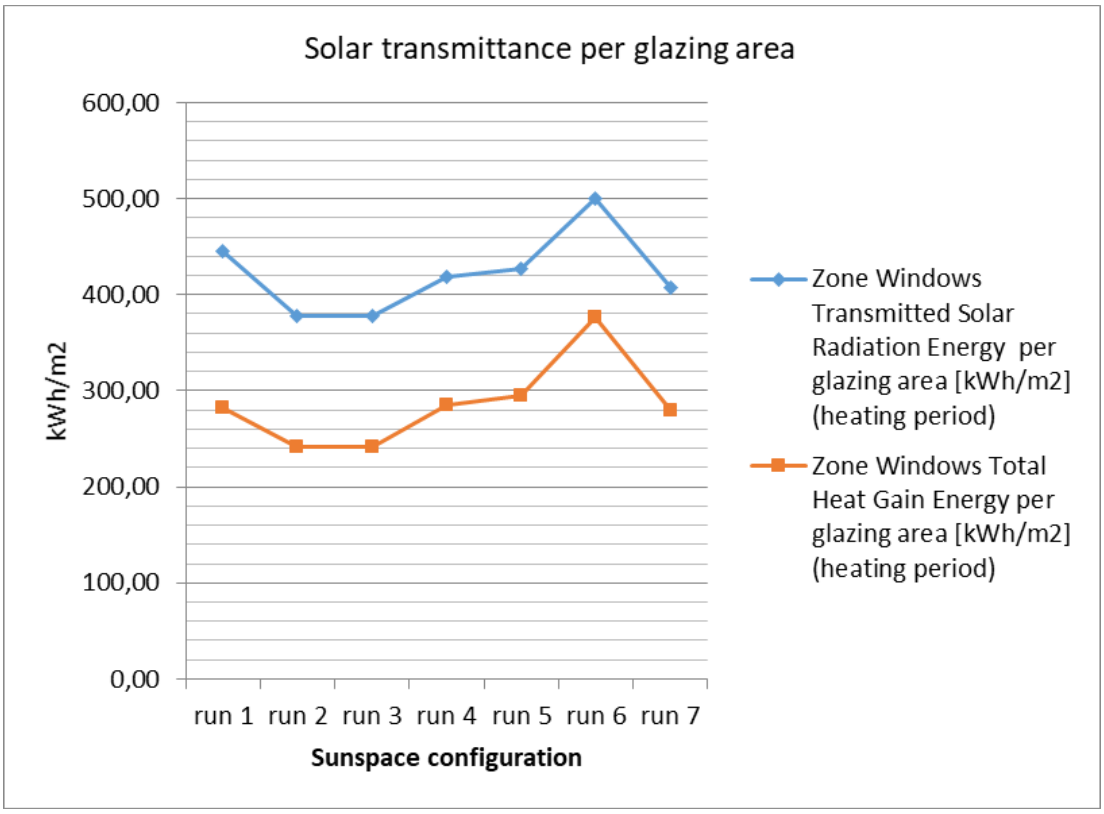


Graph 13. Percentage Change in energy needs among the different configurations

As the Graphs 12 & 13 depict, the first configuration, in which the sunspace area is attached along the southern facade of the apartment, has the lowest annual energy needs per m^2 conditioned of area, 98,39 KWh/m^2. The configuration number 6 is the second best with annual energy needs of 100,30 98,39 KWh/m^2. All the other configurations simulated had an annual energy need of 104 KWh/m^2 or more. By taking a closer picture to the table, it is noticeable that even if the first configuration has the lower annual heating demands at the same time it also has the highest cooling demand among the configurations tested. This result was quite the expected one, since in this configuration the total glazing of the sunspace was 51,00m^2, the biggest among those tested and therefore the amount of solar radiation that enters the sunspace is the higher. In fact, the solar zone windows total transmitted radiation energy in the first run is more than double of the radiation transmitted in run 6 (Graph 14).



Graph 14. Annual Solar transmittance and heat gain.



Graph 15. Solar transmittance per glazing area (kWh/m^2)

After calculating the solar radiation transmitted through the glazing and the portion of solar energy that was transformed into heat area, we notice that the configuration 6 is the most efficient among those tested, as it not only receives the highest amount per m^2 of glazing area but also utilizes the biggest portion of it (Graph 15). However, if we consider that the intention is to maximize solar potential and heat gains in total numbers, the configuration 1 remains by far the best choice.

4.3 Sunspace glazing materiality parametric energy simulation

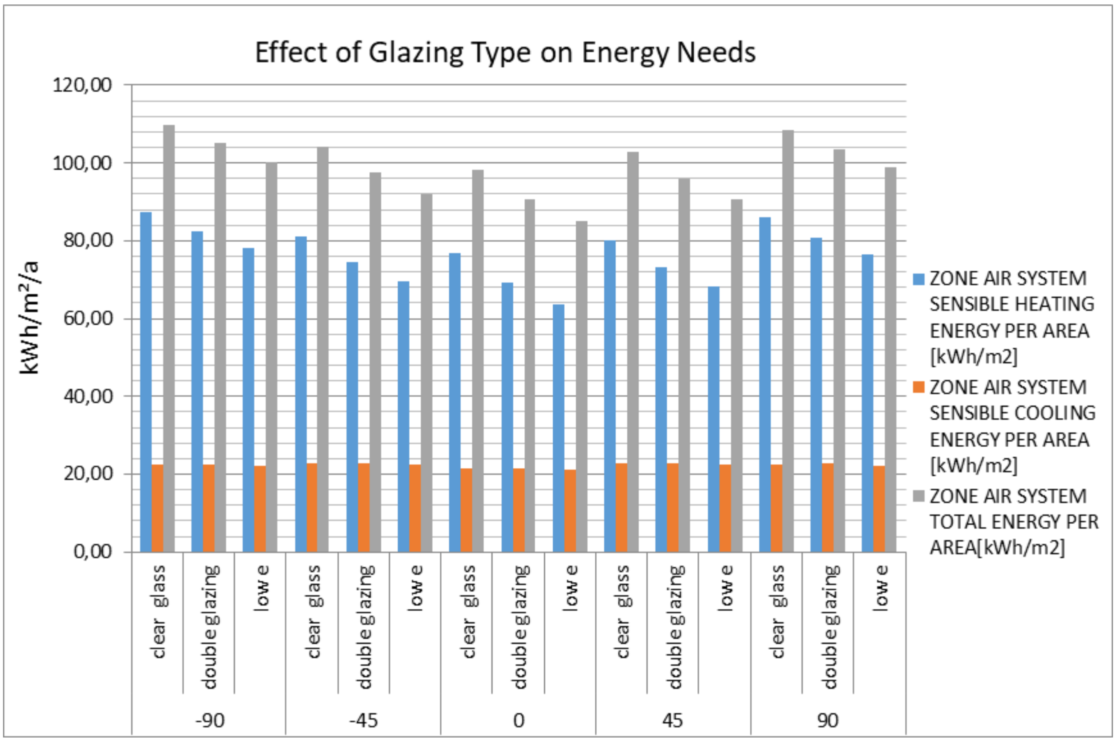
Glazing is one of e the most decisive factors that contribute to the performance of the sunspace and d to the passive solar systems in general. The type of the glazing determines not only the amount of solar energy that the system collects but also energy conservation. The glazing types that were tested are the following:

- Clear 4mm glass
- Double clear 4mm glass with an 1,6 mm air gap.
- Double glazing consisting of a clear 4mm glass and a low-e pane as the inside layer with an 1,6 mm air gap.

Another configuration tested regarding the glazing is the moveable shading. The exposure of the sunspace area to the solar radiation during summer results to high cooling needs. Therefore, the appliance of a shading device, like blinding or a curtain, device can contribute into reducing them.

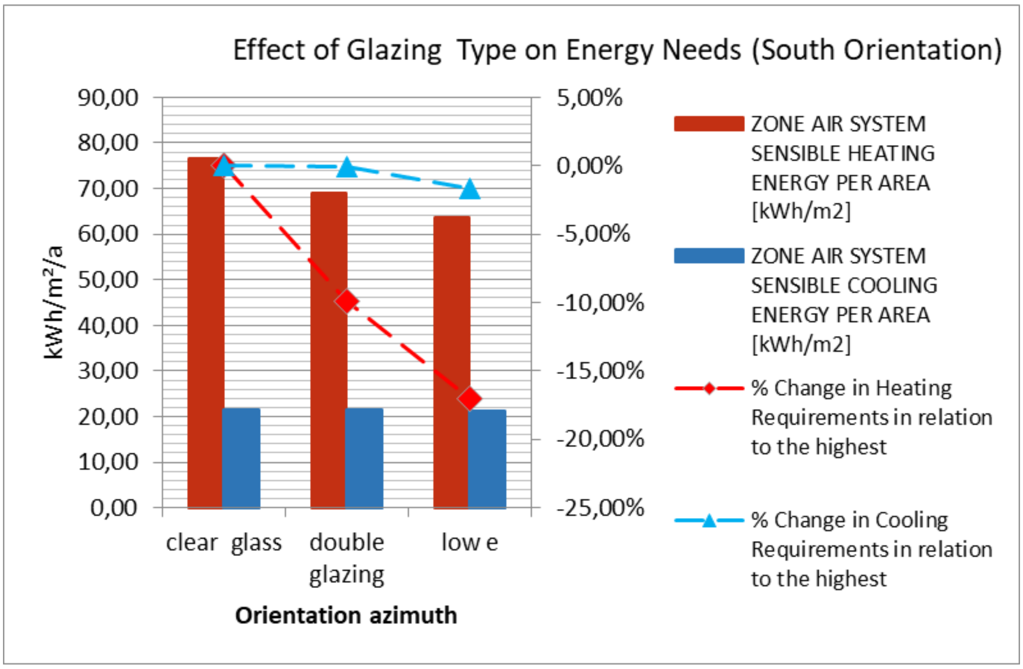
4.3.1 Glazing material effect

The first step was to investigate the energy performance of the three type of glazing in relation to the orientation. In all the orientation (West, Southwest, South, Southeast and East) the double glazing with the low e pane performs the best (Graph 16).



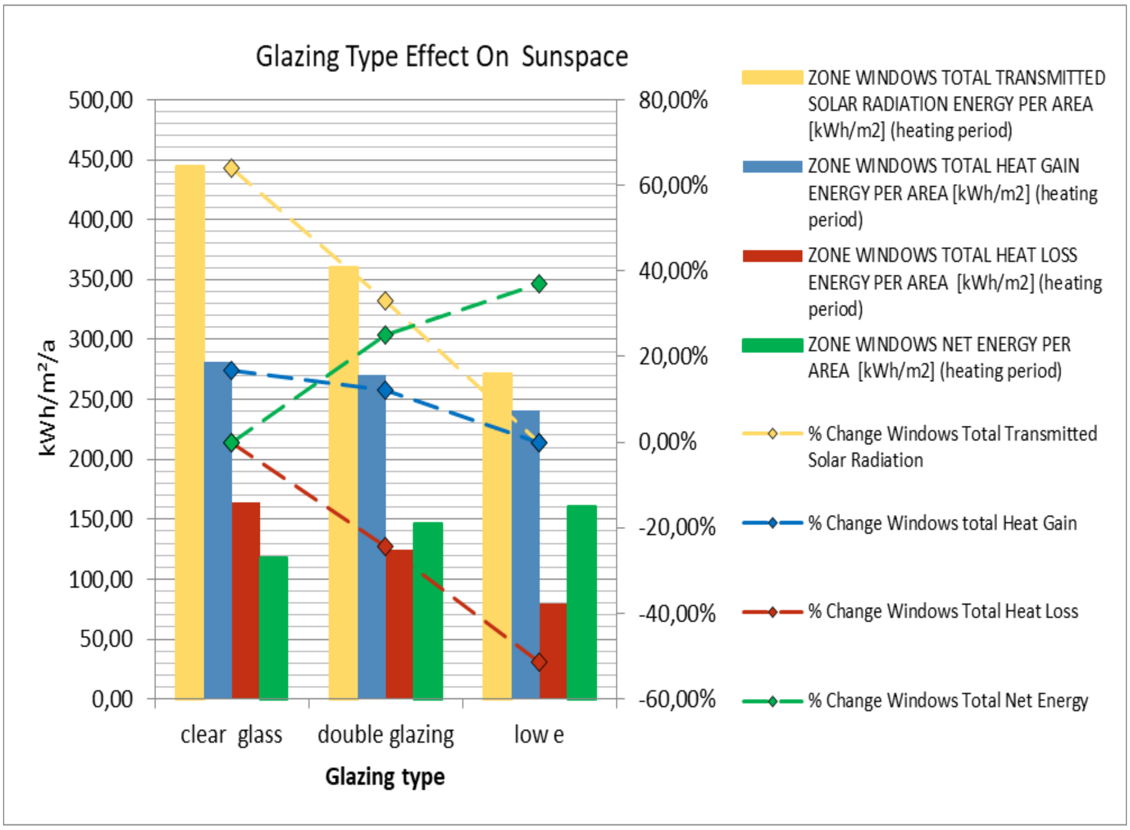
Graph 16. Annual apartment needs, orientation and glazing parametric simulation(kWh/m^2)

As the Graph 17 shows the application of the low e pane in the interior layer of the glazing type it mainly affects the heating demands of the apartment. In comparison to the single clear glass glazing the reduction of the energy required can reach up to 17,5%. The cooling demand, although, can be decreased around 2,5%.

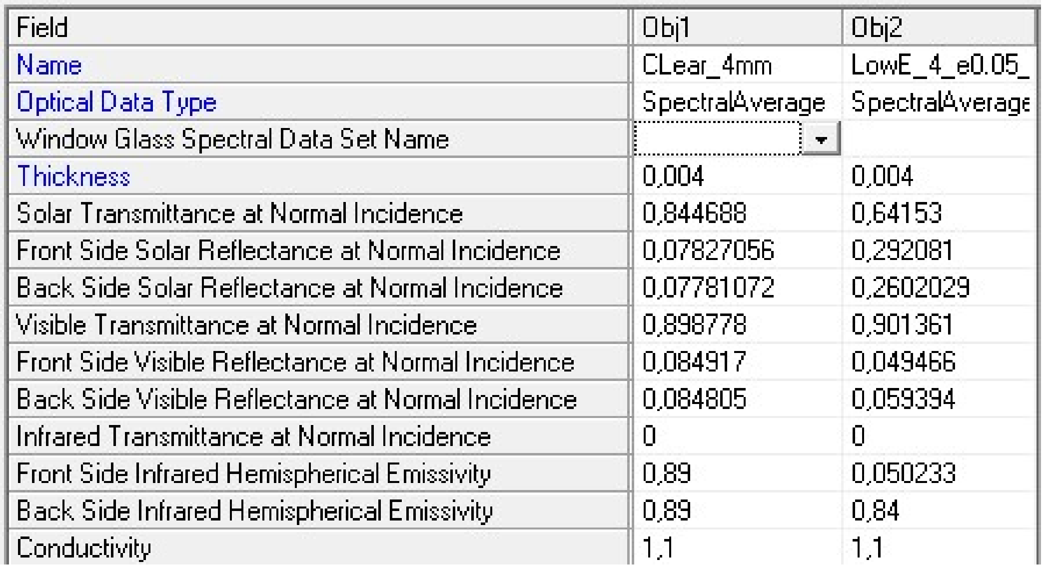


Graph 17. Effect of glazing type on apartment's annual energy needs(kWh/m^2). The values correspond to the south orientated sunspace.

Of course, this behavior can be attributed to the characteristics of the low pane. The 4mm low e pane has lower solar transmittance, higher solar reflectance and lower infrared emissivity than the clear 4mm glass (Figure 21). As a result, while the amount of annual solar radiation that enters the sunspace when the low-e pane is applied can be reduced up to 60%, the total amount of heat gains produced by the sunspace are only 17% lower. Furthermore, the low emissivity contributes to the minimization of the annual heat losses, that can be reduced in half. Consequently, the annual Net Energy that the glazing contributed to the sunspace can be calculated around 35% more when the low-e pane is applied compared to the single pane clear glass glazing (Graph 18).



Graph 18. Annual apartment needs, orientation and glazing parametric simulation(kWh/m^2)

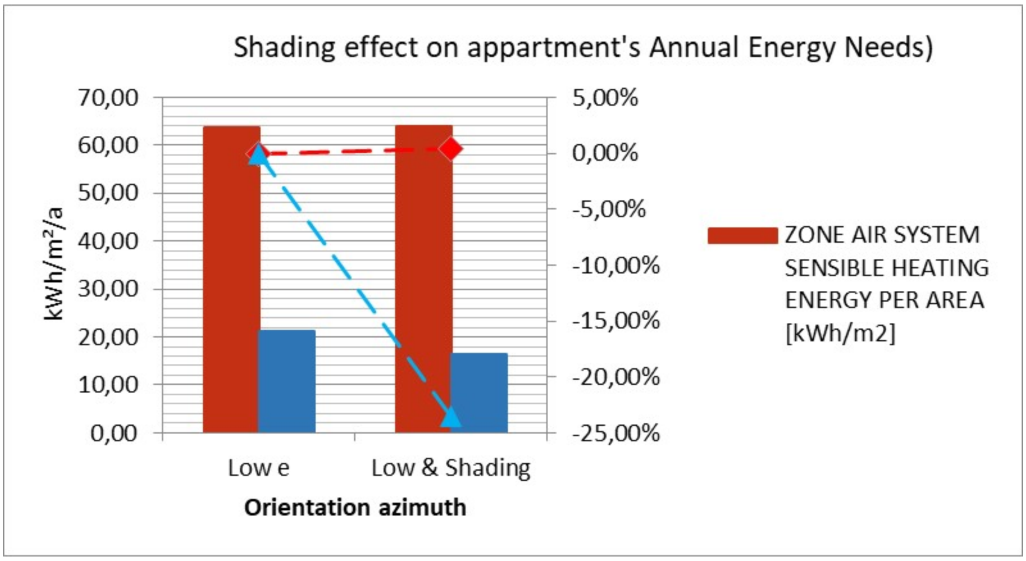


Field	Obj1	Obj2
Name	CLear_4mm	LowE_4_e0.05_
Optical Data Type	SpectralAverage	SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	0,004	0,004
Solar Transmittance at Normal Incidence	0,844688	0,64153
Front Side Solar Reflectance at Normal Incidence	0,07827056	0,292081
Back Side Solar Reflectance at Normal Incidence	0,07781072	0,2602029
Visible Transmittance at Normal Incidence	0,898778	0,901361
Front Side Visible Reflectance at Normal Incidence	0,084917	0,049466
Back Side Visible Reflectance at Normal Incidence	0,084805	0,059394
Infrared Transmittance at Normal Incidence	0	0
Front Side Infrared Hemispherical Emissivity	0,89	0,050233
Back Side Infrared Hemispherical Emissivity	0,89	0,84
Conductivity	1,1	1,1

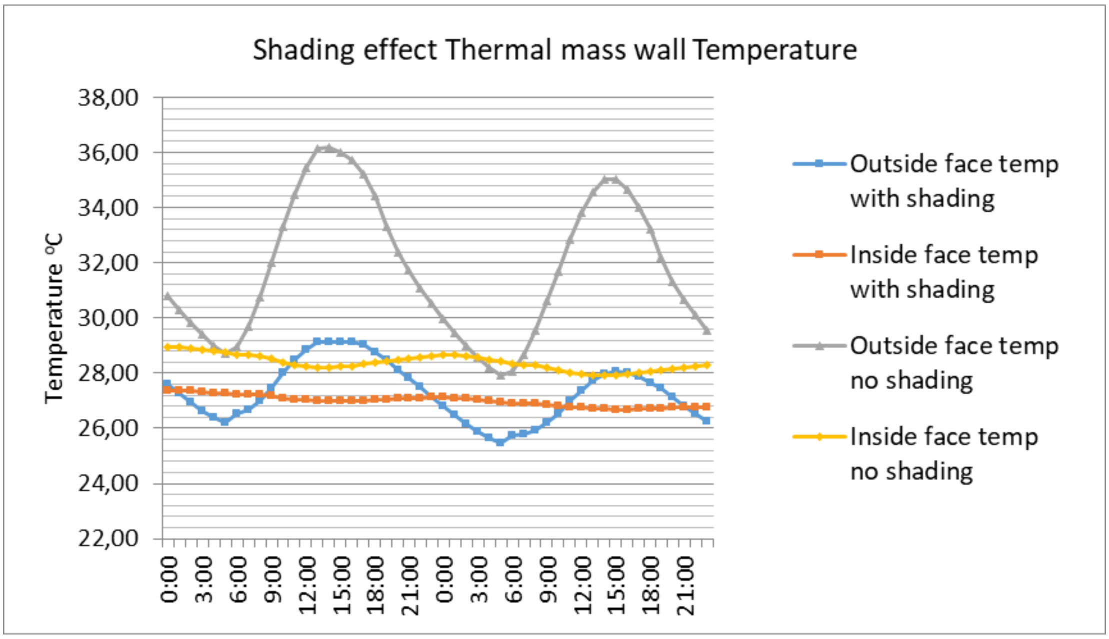
Figure 21. Glazing materials characteristics. (screenshot from the EnergyPlus software)

4.3.2 Shading effect

The last scenario tested concerning the glazing energy behavior was the application of moveable shading. A new schedule was created for the purpose the "Sc. Shading On". The shading was applied on all the sunspace glazing surfaces during the cooling period from 08:00 to 20:00 every day. As the Graph 19 depicts the heating energy needs remain unaffected while the Cooling energy needs recorded an almost 25% reduction.



Graph 19. Shading effect on Annual apartment needs (kWh/m^2)



Graph 20. Thermal mass inside and outside face temperature. Scenarios with low e glazing with and without shading.

Graph 20 depicts the magnitude of the moveable shading effect on the energy behavior of the thermal mass wall. The dates chosen were the 14rth and 15ft of July. The temperature difference of the outside surface can reach at its peak, around 15:00, almost 7ºC, between the two scenarios tested. Furthermore, even during the night, when the solar radiation is absent, the thermal mass remains around 2ºC cooler at the scenario with the moveable shading. The difference regarding the inside surface of the thermal mass wall is not that profound as the outside surface, although the 1ºC to 1,5ºC temperature difference can have a great impact on the indoor thermal conditions and on the thermal comfort consequently. Nevertheless, this temperature difference is more than enough to cause a 25% decrease of the cooling needs of the apartment.

4.4 Sunspace thermal mass wall/thermal mass floor parametric energy simulation analysis

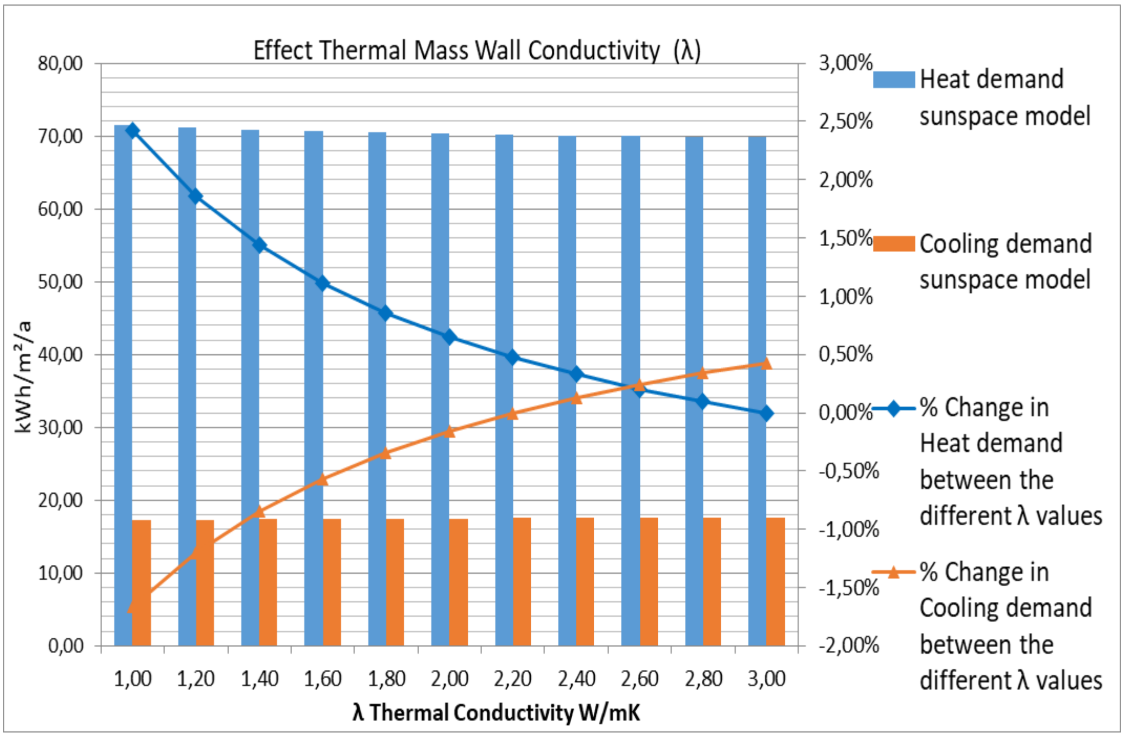
Since the sunspace is an indirect heating system the heat needs a transfer medium in order be to The prevailing factor that defines the amount of solar radiation transmitted thought the glazing that will transformed into useful heat is the thermal characteristics of the thermal mass wall. The role of the wall is to accumulate the solar radiation, store it in the form of heat and then release it to the adjoining space. Some of the parameters that affect the energy behavior of the thermal mass wall are the absorptance, the conductivity of the material, the density and the thickness, the presence or absence of thermal insulation etc. The following series of simulations aim to configure the optimal thermal wall characteristics. The model used is consists of the low e glazing and the moveable insulation applied on it.

4.4.1 Conductivity parametric simulation

The first parameters that was put into test was the conductivity (λ) of the thermal mass wall. The criteria for the comparison was the annual heating and cooling energy needs of the apartment, that are presented in the following graph. The values for the conductivity range between 1,0 - 3,0 W/mK with a step of 0,2 W/mK.

				Percentage change comparing to the lowest (%)	
	λ thermal conductivity W/mK	Heat demand sunspace model	Cooling demand sunspace model	% Change in Heat demand between the different λ values	% Change in Cooling demand between the different λ values
run 1	1,00	71,56	17,22	2,42%	-1,67%
run 2	1,20	71,17	17,31	1,86%	-1,20%
run 3	1,40	70,88	17,37	1,44%	-0,84%
run 4	1,60	70,65	17,42	1,11%	-0,56%
run 5	1,80	70,47	17,46	0,86%	-0,34%
run 6	2,00	70,33	17,49	0,65%	-0,16%
run 7	2,20	70,21	17,52	0,48%	0,00%
run 8	2,40	70,10	17,54	0,33%	0,13%
run 9	2,60	70,01	17,56	0,20%	0,24%
run 10	2,80	69,94	17,58	0,10%	0,34%
run 11	3,00	69,87	17,59	0,00%	0,43%

Table 8. Results of thermal mass wall conductivity (λ) parametric energy simulation



Graph 21. Effect of thermal mass wall conductivity on apartment's annual energy needs(kWh/m^2/a)

Graph 21 shows that the decisive value of the thermal wall conductivity in order to optimize its efficiency is around 2,60 W/mK. The material with a conductivity value close to the optimal one is a material very common in building construction the reinforced concrete 2,60 W/mK. Consequently, for the forthcoming simulations regarding the behavior of the thermal mass the reinforced concrete will be the material applied.

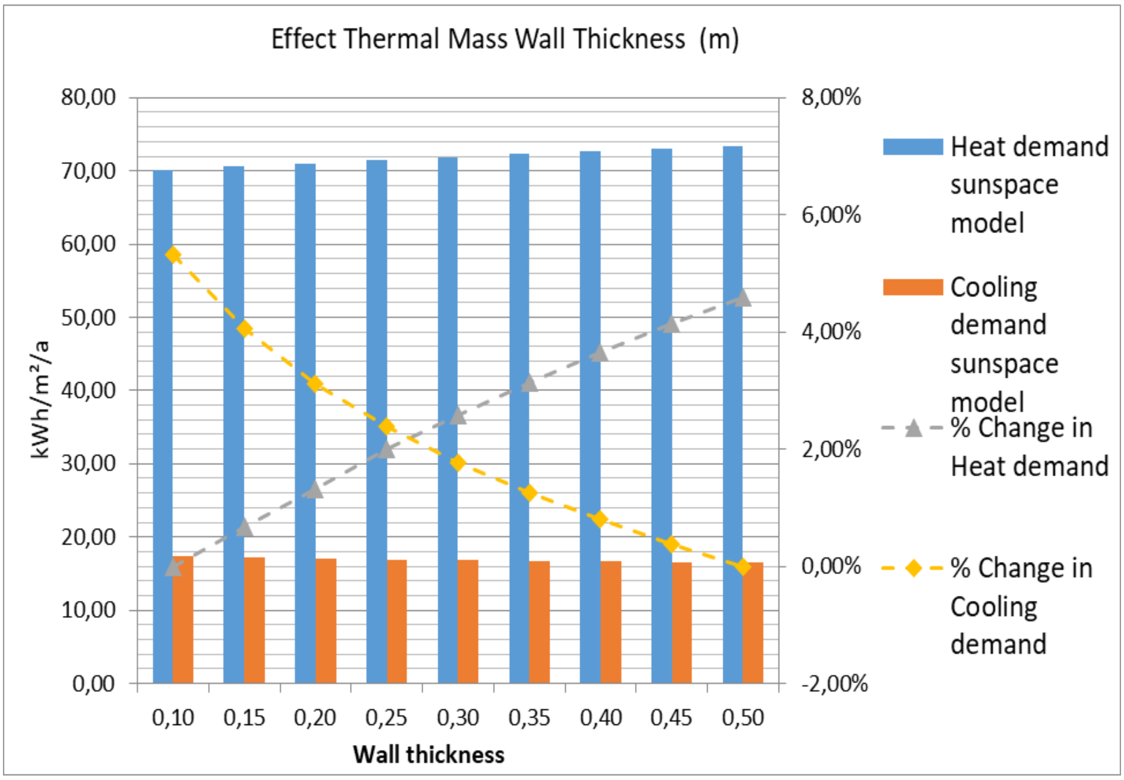
4.4.2 Thermal mass thickness

The thermal wall thickness determines its thermal inertia, a basic attribute concerning the effect that the wall has on the heat storage and distribution in a passive system. In the original model the thermal mass wall consisted of a clay brick 9cm and a layer of plaster on both sides. In the parametric simulation the material wall is reinforced concrete ranging from 10cm to 50cm with a 5cm step. The desired wall thickness would be the one that achieves the lowest energy needs for the apartment but also the one that delivers heat into it during the period of the day with the highest need.

Table 9 and graph 22 show that by increasing the thickness of the thermal mass wall the heating needs also increase while the cooling decrease. This can be attributed in two points. The first one is that by increasing the thickness the thermal inertia of the wall also increases requiring absorbing and storing more heat. During winter this heat is gained from the interior, thus the heating needs raise and during summer the wall absorbs more heat from the sunspace area and prevents it from entering the interior of the apartment. The other fact is that the thermal wall is not insulated, meaning that the heat it has gained throughout the day during summer is not entirely transferred towards the apartment during the hours with no solar radiation.

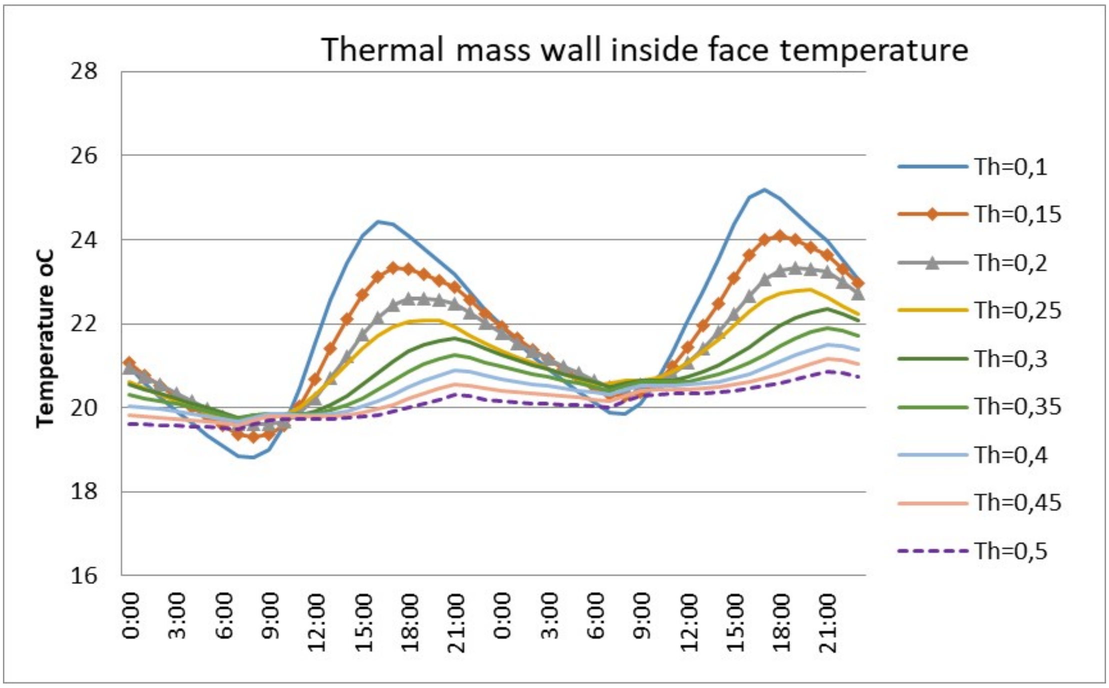
		Apartment's annual energy needs		Percentage change (%)	
	Wall thickness(m)	Heat demand sunspace model	Cooling demand sunspace model	% Change in Heat demand	% Change in Cooling demand
run 1	0,10	70,08	17,41	0,00%	5,33%
run 2	0,15	70,55	17,20	0,68%	4,06%
run 3	0,20	70,99	17,04	1,31%	3,12%
run 4	0,25	71,47	16,92	1,99%	2,38%
run 5	0,30	71,89	16,82	2,59%	1,77%
run 6	0,35	72,27	16,73	3,14%	1,25%
run 7	0,40	72,64	16,66	3,65%	0,79%
run 8	0,45	72,98	16,59	4,14%	0,39%
run 9	0,50	73,30	16,53	4,60%	0,00%

Table 9. Results of thermal mass wall thickness (m) parametric energy simulation

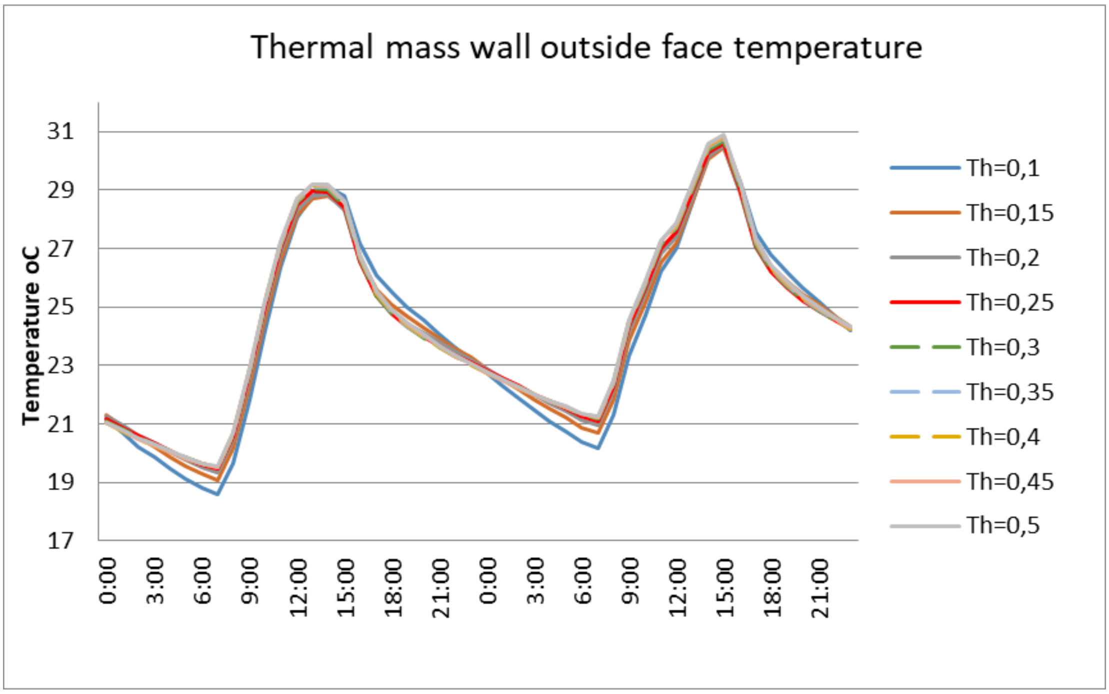


Graph 22. Effect of thermal mass wall thickness on apartment's annual energy needs(kWh/m^2/a)

Graphs 23 and 24 shows the inside and outside face temperature of the thermal mass wall for the various thickness values tested. The first observation is that the thickness does not affect the outside face temperature, since the temperatures reached are similar and at the same time during a winter day (12/12-13/12). On the other hand, as shown in the graph 23 the wall thickness plays a significant role on the inside face temperature. As the wall gets thicker, the temperature deviation becomes smaller. So for the 50cm thick wall the temperature ranges between 19,5ºC to 20,5 ºC. On the contrary the for the 10cm thick wall the temperature ranges between 18,5ºC to 24,5 ºC. Although neither of these options is the optimal one. In order to have the desires thermal comfort conditions inside the apartment we need a wall temperature around 21ºC to 22ºC throughout the day without a great deviation. So the best choice would be the 15cm or 20cm thick reinforced concrete wall.

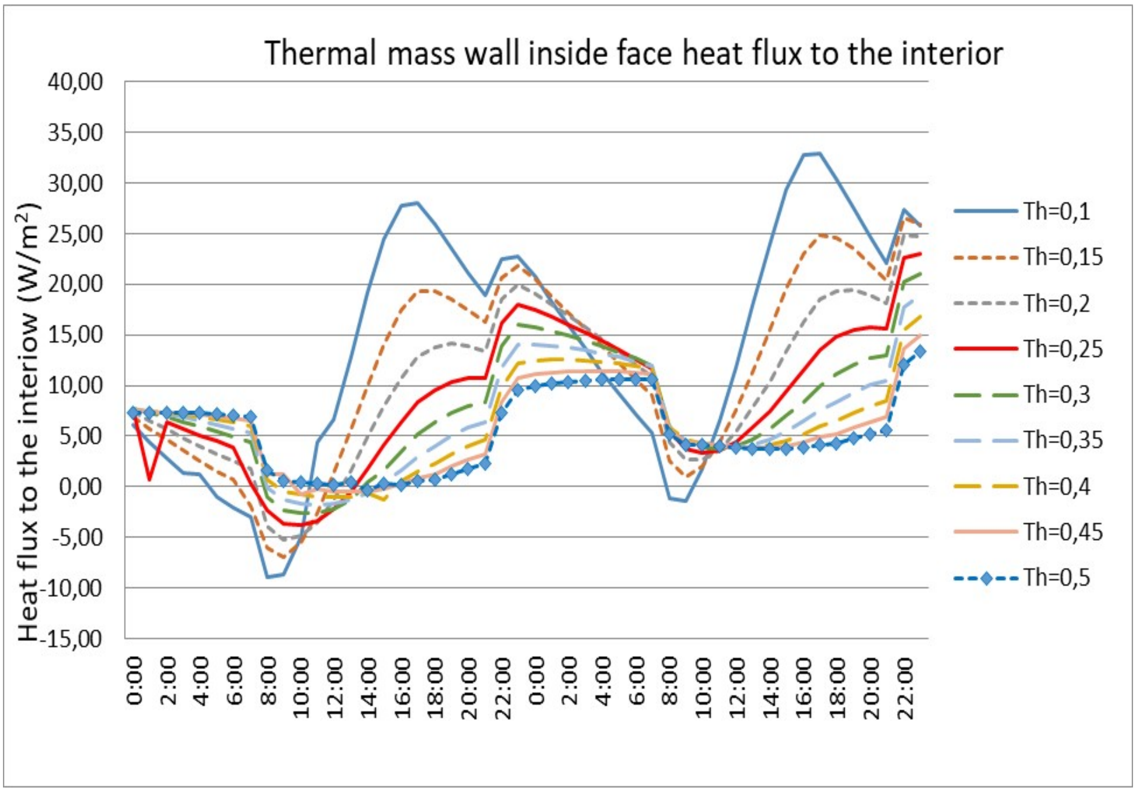


Graph 23. Thermal mass wall inside face temperature for various wall thickness.



Graph 24. Thermal mass wall outside face temperature for various wall thickness.

A very crucial feature of the thermal mass wall concerning its effect on the reduction of the heating needs is the amount of the solar radiation that actually distributes into the apartment and when. Graph 25 shows the heat flux of the thermal mass wall to the interior for the various thicknesses tested. We can easily notice that the 10cm wall has the lowest time lag between absorbing the solar radiation and attributing to the interior while the 50cm thick wall has the highest. In fact, the 50cm thick wall distributes the heat during that period of the day that is no longer needed, between 22:00 and 8:00 of the next day. The time period that the apartment needs gain heat from the thermal mass wall is after the sunset, between 17:00 until 21:00. Consequently, for a non-insulated thermal mass wall the 15cm and the 20cm seem to be the optimal thick values.



Graph 25. Thermal mass inside face heat flux to the interior. (W/m^2)

5 Energy performance simulation of the sunspace under different European climates

The following simulations aim to investigate the energy performance of a typical sunspace as a function of the climatic conditions of 8 different European cities. Similar studies have shown that the sunspace is a passive solar system that is more effective in reducing energy needs during the heating period. In the contrary hot climates and high temperatures cause problems of overheating.(Mihalakakou, 2002). Even in temperate climates the design of the sunspace has to take into consideration the climatic conditions in order to maximize its effectiveness.

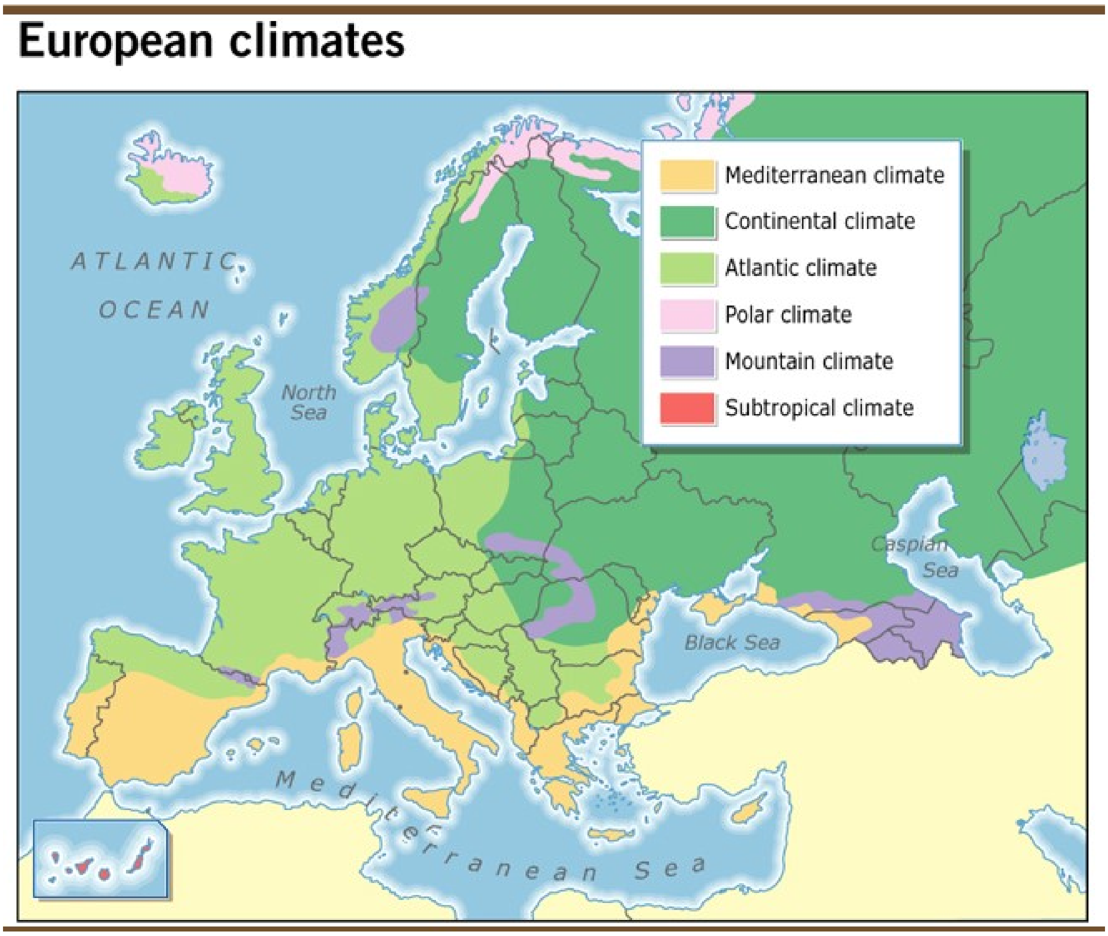


Figure 22. Climate classification map of Europe

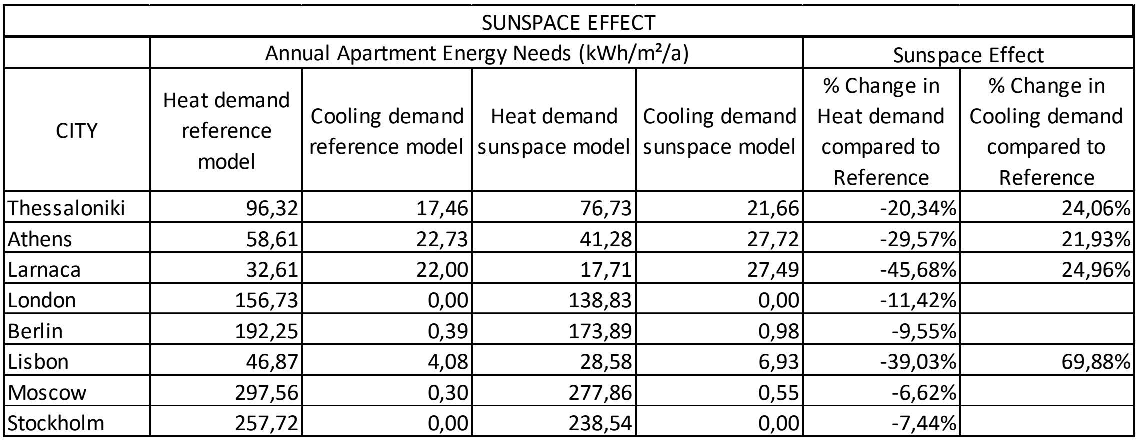
As the figure 22 shows most of the Southern Europe belongs to the Mediterranean climate zone which features very hot summers, mild winters, less rainfalls and a lot of sunny skies. The sun potential at these areas are high, so all passive solar systems, including the sunspace, can have high efficiency as energy saving measures. The Western part of Europe which includes the northern parts of Portugal and Spain, the Great Britain, France, Germany etc., have an Oceanic climate with cool winters and summers, frequent overcasts and more rainfalls. In the Central and Eastern Europe, the prevailing climate is the Continental with cold winters, hot summers and large annual ranges of temperatures.

The cities chosen for the energy simulations of this cover all the different climatic conditions of Europe. Thessaloniki and Athens were chosen from Greece to investigate the difference to indicate the effect that the local microclimate can have on the sunspace design even between two areas that belong to the same country. The city of Larnaca was chosen from Cyprus which is one of the hottest areas of Europe, Lisbon, London and Berlin, and finally Moscow and Stockholm which represent the colder areas of Europe.

All the climatic data files were downloaded from the Energy Plus official site. In all simulations the nigh ventilation technique and sunspace glazing shading during the summer days were taken as a given to avoid overheating.

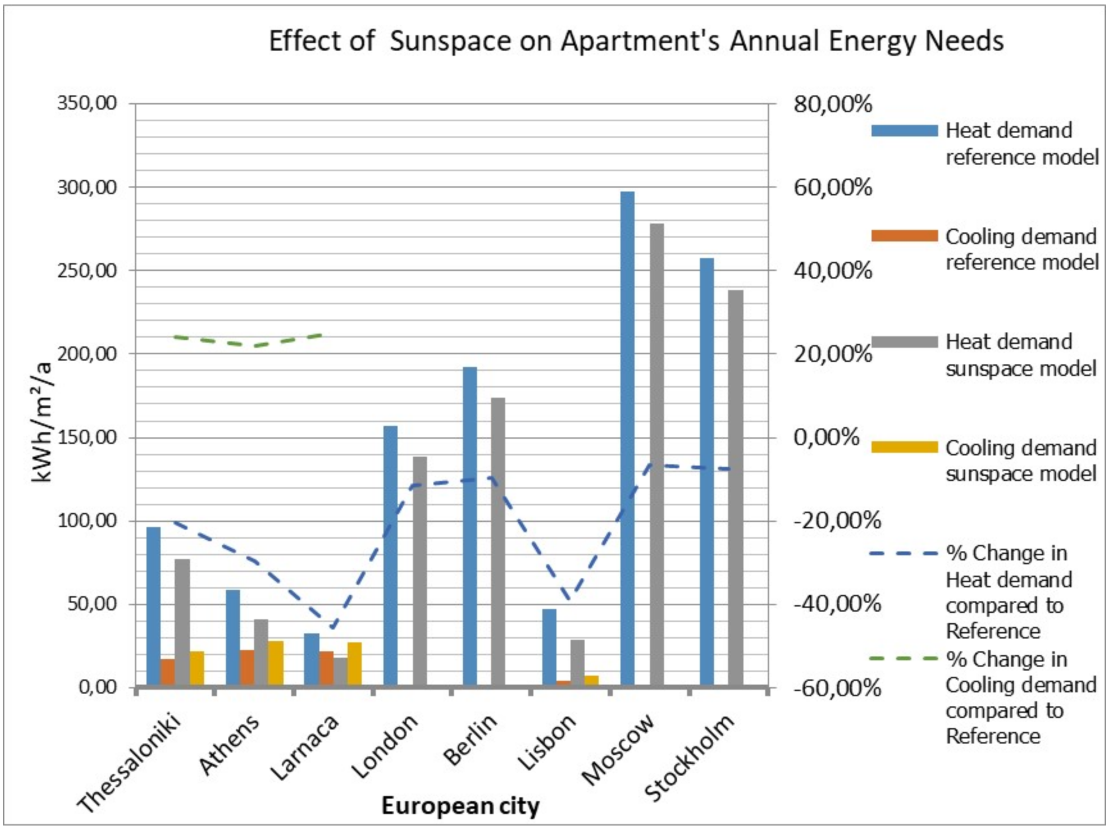
5.1.1 Sunspace efficiency

Graph 26 and Table 10 shows that the passive solar sunspace is more efficient in the cities with hotter climates. In Lisbon, Larnaca and Athens the application of a sunspace can reduce the heating demand up to 45 %, while in areas with lower sun potential and higher heating needs the reduction by the sunspace application ranges between 7-12%. Regarding the cooling needs, for the cool climates they are zero or negligible. On the opposite, the cooling needs raise for the hotter climates due to the sunspace adding about 4-6KWh/m^2/a for the examined apartment.



SUNSPACE EFFECT						
	Annual Apartment Energy Needs (kWh/m²/a)				Sunspace Effect	
CITY	Heat demand reference model	Cooling demand reference model	Heat demand sunspace model	Cooling demand sunspace model	% Change in Heat demand compared to Reference	% Change in Cooling demand compared to Reference
Thessaloniki	96,32	17,46	76,73	21,66	-20,34%	24,06%
Athens	58,61	22,73	41,28	27,72	-29,57%	21,93%
Larnaca	32,61	22,00	17,71	27,49	-45,68%	24,96%
London	156,73	0,00	138,83	0,00	-11,42%	
Berlin	192,25	0,39	173,89	0,98	-9,55%	
Lisbon	46,87	4,08	28,58	6,93	-39,03%	69,88%
Moscow	297,56	0,30	277,86	0,55	-6,62%	
Stockholm	257,72	0,00	238,54	0,00	-7,44%	

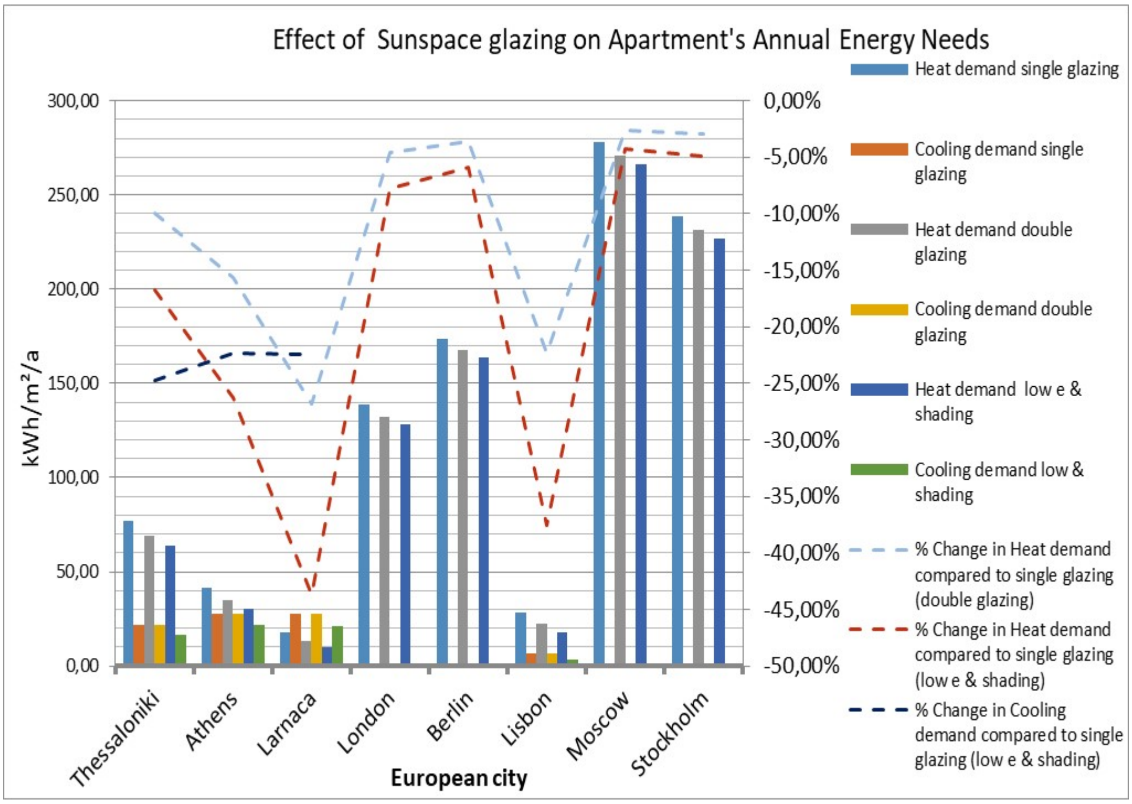
Table 10. Effect of Sunspace on Apartment’s Annual Energy Needs.



Graph 26. Effect of Sunspace on Apartment’s Annual Energy Needs.

5.1.2 Glazing effect

Three different glazing constructions where tested for their efficiency in every selected area. The first consists of a single clear glass pane, the second of two panes with an air gap in between and the third of two panes, with a low e coating on the outside face of the interior pane and shading. As the graph 27 shows the higher the sun potential of the area the higher the effect of the interventions proposed. The double glazing and the low coating can reduce up to 45% of the annual heating demand of the apartment in Larnaca, while in Moscow, Stockholm and Berlin only around 5%. Such a small annual energy demand reduction cannot justify the construction cost of the double glazing or the low coating, so the single plane glazing seems to be the one-way solution regarding the sunspace glazing.



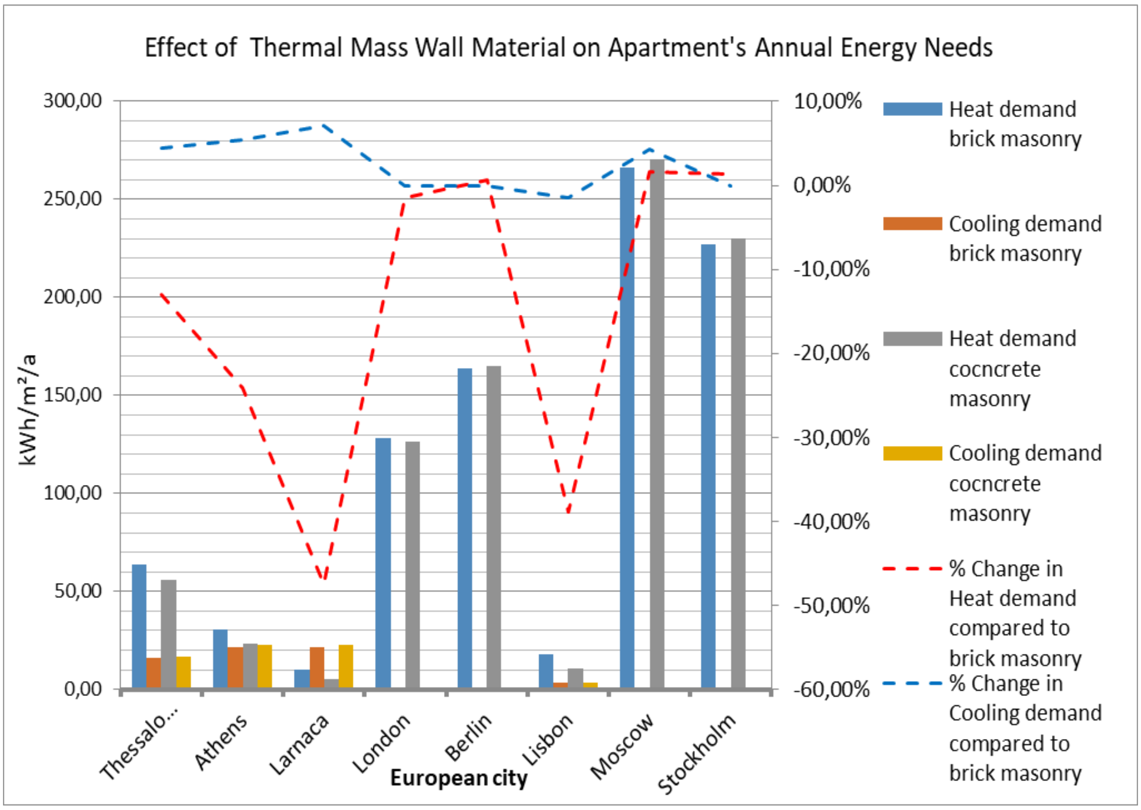
Graph 27. Effect of Sunspace glazing on Apartment’s Annual Energy Needs.

5.1.3 4.2 Thermal mass wall effect

Wall material conductivity (λ)

The first parameter that was tested was the conductivity (λ) of the thermal mass wall. According to the results of the parametric simulations that were presented in chapter 4 of the dissertation about the optimum conductivity of the thermal mass wall material, concrete was the optimum choice for the climate of Thessaloniki. Therefore, the first set of energy simulations compares the behavior of the 24cm thick brick wall and the 24cm thick concrete wall under the different European climates. The criteria for the comparison was the annual heating and cooling energy needs of the apartment, that are presented in the graph 28.

Graph 28 shows that the concrete wall performs better in hot climates than in cold ones. In more detail the apartments in Larnaca and in Lisbon had a decrease of about 40% in their heating energy needs, the one in Athens 24% and in Thessaloniki 13%. On the contrary the apartment located in London reduced its needs only by 1,5%, while those in Berlin, Moscow and Stockholm increased their heating energy needs when the concrete wall was applied. In regard of the cooling needs, in hot climates the simulation resulted in a small raise of about 4% - 7% while in cold climates the cooling needs were none or negligible.

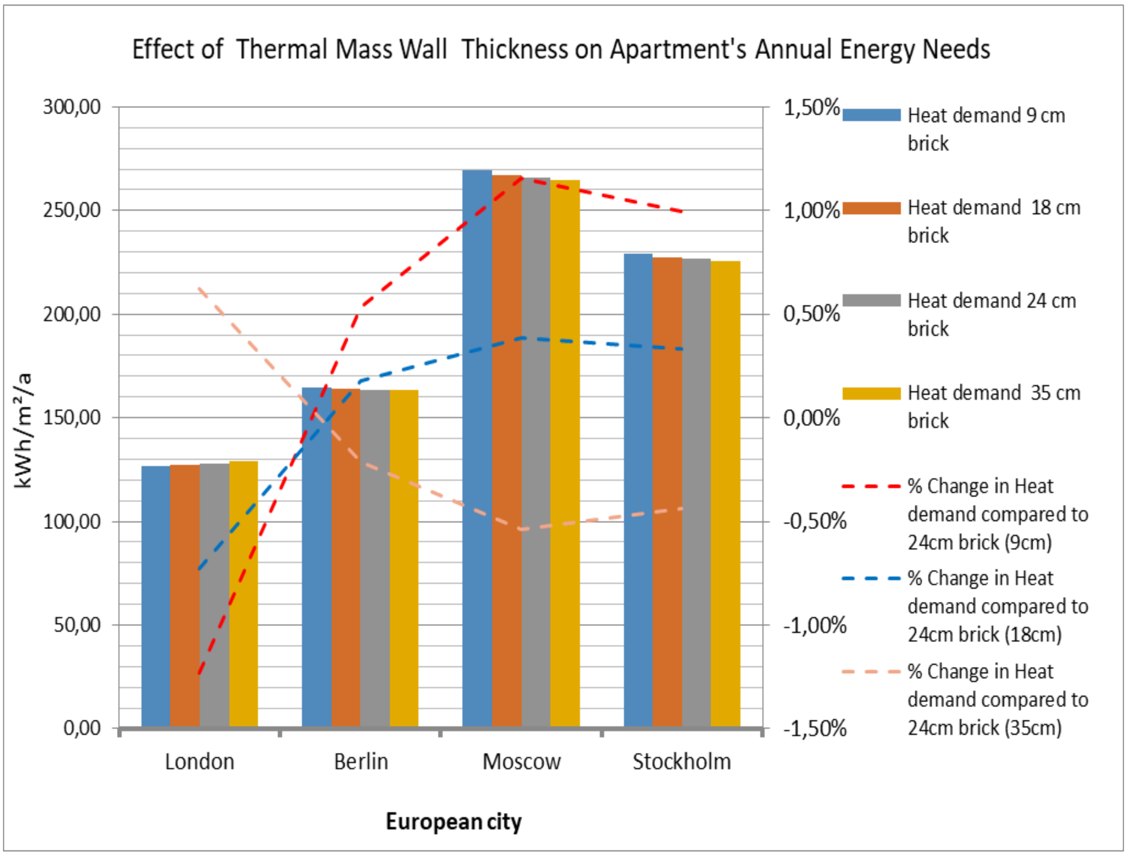


Graph 28. Effect of the Thermal Mass Wall Material on Apartment's Annual Energy Needs.

Wall thickness

Since the concrete wall had negative effect on the energy behaviour of the sunspace in cold climates, the second series of simulation investigate the effect of the thermal mass wall thickness. The wall material for all simulations is the clay brick. The parametric simulation includes 4 runs with different wall thickness, 9cm, 18cm, 24cm and 35cm. The results are presented in Graph 29.

The wall thickness had no great effect on the apartments energy need. The deviations were no greater than 2,00%. The sunspace located in London performed better with the 9cm thick brick wall while the ones located in Berlin, Moscow and Stockholm with the 35cm thick brick wall.



Graph 29 Effect of the Thermal Mass Wall Thickness on Apartment's Annual Energy Needs.

6 Conclusions

The environmental design of a building is an emerging issue that concerns Europe the past few decades. The design of an energy efficient building is a complex procedure that requires combination of various parameters in order to achieve optimization. The use of energy simulation and form optimization processes is proved that can improve the architectural synthesis process by providing the designers with useful tools that help them face the task in a more holistic way. These tools can explore and compare all the alternatives of space design and be the groundwork for performance based decisions in the early stages of the design process.(Touloupaki and Theodosiou, 2017b).

This paper investigated and presented an analysis of the main operations of the passive solar sunspace and then a parametric analysis of its energy performance based on a series of simulations using the EnergyPlus software. The reference model that all the simulation was based was an apartment, part of typical urban multi-story residential building in Greece, called "polykatoikia". The objective of every optimization test was to achieve minimum annual heating and cooling needs of the adjoining apartment. All simulation predicted that the application of the sunspace could significantly contribute to the reduction of the apartment's heating needs during winter while, in some cases, creating overheating problems during summer.

Several parameters that effect the efficiency of the passive solar sunspace were investigated, including the orientation, the various forms and degrees of integration to the apartment's design, the type the glazing, the material and the thickness of the common wall. The analysis of the quantified data that was produced by the energy simulations showed which parameter combinations enhance the efficiency of the sunspace.

Orientation

The South orientated sunspace performed better than those orientated towards East or South. The outcome of the orientation parametric simulation was the expected once, since all passive solar systems operate in the optimum way when facing South. The amount of solar radiation that enters the sunspace is the maximum and so are the solar heat gains. A slight deviation from South orientation no more than 20° degrees does not affect the energy performance of the sunspace significantly.

Glazing

The type and the area of the glazing is the most important parameter of the sunspace, since it not only determines the amount of useful solar radiation but has a significant effect on the heat losses at the same time. The use of the second pane in glazing along with the existence of the air gap can reduce the heat losses through the sunspace glazing up to 20%, while with the low e coating the reduction can surpass 45%.

Common wall

The role of the common wall is to store and distribute the heat to the adjoining building. Thermal conductivity, thermal absorptance and heat capacity are the main characteristics that effect the energy performance of the common wall. For hot climates concrete walls perform while for cold climates the brick wall is the best choice. In order to maximize the benefits of the thermal mass the heat needs to be distributed to the adjoining apartment when the sun is set and the outdoor temperature drops. The parameter that determines the time delay between heat storage and heat distribution is the common wall thickness. Very thick thermal mass may take too long top heat while thin thermal mass may distribute heat when it is not needed. The optimum concrete wall thickness for hot climates ranges between 15-20 cm, which can absorb adequate heat during the day and distribute it during late in the evening, according to the hourly analysis. On the other hand, the common wall needs to be thin for cold climates since the solar potential is significantly lower.

Overheating

In order to achieve optimization of the sunspace throughout the year, the overheating problem had to be solved. For that cause two passive techniques were used, the night ventilation technique and the external shading of the sunspace glazing during the summer days. Those two techniques proved to significantly improved the energy performance of the sunspace.

Climate parameter

The passive solar sunspace is a more suitable as an energy saving measure in areas like Thessaloniki, Athens, Lisbon and Larnaca that are located in Southern Europe and in the Mediterranean climate zone than in cold climates like Berlin, Stockholm and Moscow. The main use of the solar sunspace is to utilize solar radiation during winter and transform it into solar heating, which have a significant impact on the energy efficiency of the apartment, reducing its energy needs up to 40% in the case of Larnaca. On the other hand, the use of the sunspace in cold climates can contribute to only 10% of the annual heating needs.

This study presented an analysis of the most common and conventional techniques used in a passive solar sunspace in order to optimize its efficiency. The research can be continued in fields like the efficiency of the common wall in relation to the glazing and opaque surfaces ratio the use of vents and other passive circulation techniques as well as the use of new insulating and phase change materials that can contribute to its overall energy performance. Moreover, further investigation regarding the cost of the proposed configurations and whether this cost can be balanced by the energy saving will help to determine the overall sustainability of the passive solar sunspace.

In any case, this study proved that the sunspace can be considered one of the most useful tools of the designers in order to achieve energy shaving by using solar radiation. As the technology develops more complex constructions and more efficient materials will contribute further into the sunspace energy optimization and into the energy needs minimization of the building sector.

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8 Appendix I

8.1 List of figures

8.2 List of graphs

8.3 List of tables

9 Appendix II

Appendix II includes a part of the simulation outputs presented in the form of tables. Due to the large amount it was not feasible to include all of them. They will be included in the excel file that will be delivered along with the other files.

		Annual Apartment Energy Needs (kWh/m²/a)			
	Orientation azimuth	Heat demand reference model	Cooling demand reference model	Heat demand sunspace model	Cooling demand sunspace model
East	-90	102,70	19,24	87,26	22,51
	-75	101,43	19,40	85,14	22,74
	-60	100,18	19,36	83,17	22,89
	-45	98,94	19,05	81,23	22,79
	-30	97,72	18,51	79,30	22,42
	-15	96,74	17,84	77,60	21,90
South	0	96,32	17,46	76,73	21,66
	15	96,53	17,62	76,97	21,88
	30	97,32	18,11	78,26	22,41
	45	98,48	18,54	79,99	22,82
	60	99,71	18,79	81,85	22,94
	75	100,99	18,81	83,84	22,79
West	90	102,32	18,66	86,04	22,57

Table 11 Effect of orientation to the annual apartment energy needs

Sunspace glazing efficiency in relation to orientation (heating period)					
	Orientation azimuth	Zone Windows Total Transmitted Solar Radiation Energy (kWh/m^2)	Zone Windows Total Heat gained (kWh/m^2)	Zone Windows Total Heat loss (kWh/m^2)	% Change in Total transmitted radiation compared to South
East	-90	531,86	332,91	203,26	-39,07%
	-75	606,40	379,18	225,71	-30,54%
	-60	676,32	423,01	247,84	-22,53%
	-45	741,43	464,83	270,26	-15,07%
	-30	801,69	504,42	292,77	-8,16%
	-15	849,83	535,97	311,47	-2,65%
South	0	872,96	552,59	322,22	0,00%
	15	864,71	551,37	323,01	-0,95%
	30	828,05	532,65	313,78	-5,14%
	45	774,42	501,25	297,32	-11,29%
	60	712,25	463,03	277,48	-18,41%
	75	642,10	418,84	254,96	-26,45%
West	90	564,58	369,10	229,94	-35,33%

Table 12 Sunspace glazing efficiency in relation to orientation

	Monthly apartment needs			
	SENSIBLE HEATING ENERGY [kWh] REFERENCE	SENSIBLE COOLING ENERGY [kWh] REFERENCE	SENSIBLE HEATING ENERGY [kWh] SUNSPACE	SENSIBLE COOLING ENERGY [kWh] SUNSPACE
January	2624,68	0.000	2224,77	0.000
February	2083,89	0.000	1732,77	0.000
March	1436,72	0.000	1052,63	0.000
April	454,31	0.000	290,15	0.000
May	0.000	8,56	0.000	23,69
June	0.000	321,17	0.000	420,30
July	0.000	685,72	0.000	838,58
August	0.000	668,87	0.000	802,32
September	0.000	131,31	0.000	167,65
October	145,51	0.000	63,00	0.000
November	1115,95	0.000	820,01	0.000
December	2156,44	0.000	1796,95	0.000
Annual Sum or Average	10017,50	1815,63	7980,28	2252,55

Table 13 Monthly apartment needs

	Orientation azimuth						
	East			South			West
	-90	-60	-30	0	30	60	90
6:00	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0
8:00	4,51	5,26	4,75	3,10	0,89	0,79	0,79
9:00	79,06	99,61	95,91	68,90	23,62	13,29	13,29
10:00	186,95	264,95	277,48	222,22	105,26	36,07	36,07
11:00	149,93	268,86	316,94	289,89	190,88	59,25	49,20
12:00	140,52	448,11	629,71	647,21	499,56	201,49	67,58
13:00	76,22	341,02	639,31	751,68	672,92	406,80	89,80
14:00	62,91	127,72	373,59	515,25	526,20	405,21	166,29
15:00	46,25	48,22	182,09	311,02	357,57	316,74	193,25
16:00	17,02	17,02	35,05	73,43	92,71	90,68	67,77
17:00	0,59	2,77	3,25	6,15	7,95	8,28	7,06
18:00	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0

Table 14 Solar transmittance through glazing

	Annual Apartment Energy Needs (kWh/m^2/a)			Geometry effect on apartment's energy needs		
	Heating demand	Cooling demand	Total energy demand	% Change in heating demand in comparison to the lowest(run 1)	% Change in cooling demand in comparison to the lowest (run 2 & 3)	% Change in total energy demand in comparison to the lowest (run 1)
run 1	76,73	21,66	98,39	0,00%	15,85%	0,00%
run 2	85,52	18,70	104,21	11,45%	0,00%	5,91%
run 3	85,53	18,70	104,23	11,46%	0,00%	5,93%
run 4	84,46	19,85	104,30	10,07%	6,16%	6,01%
run 5	84,03	19,88	103,90	9,51%	6,31%	5,60%
run 6	80,70	19,61	100,30	5,16%	4,87%	1,94%
run 7	85,35	19,94	105,29	11,23%	6,66%	7,01%

Table 15 Geometry effect on apartment's energy needs

Geometry effect on sunspace efficiency					
	Zone Windows Transmitted Solar Radiation Energy per glazing area [kWh/m^2] (heating period)	Zone Windows Total Heat Gain Energy per glazing area [kWh/m^2] (heating period)	% Change in Zone Windows Transmitted Solar Radiation	% Change in Zone Windows Total Heat Gain Energy	% of Solar Radiation transmitted that transformed into Heat Gain
run 1	445,04	281,71	0,00%	0,00%	63,30%
run 2	377,95	242,21	-15,08%	-14,02%	64,08%
run 3	378,05	242,30	-15,05%	-13,99%	64,09%
run 4	418,56	285,47	-5,95%	1,33%	68,20%
run 5	427,69	294,50	-3,90%	4,54%	68,86%
run 6	499,85	376,05	12,32%	33,49%	75,23%
run 7	407,02	279,16	-8,54%	-0,91%	68,59%

Table 16 Geometry effect on sunspace efficiency