Department of Mechanical Engineering

EF900 – Individual MSc Project

Identification and evaluation of critical parameters regarding thermal gains and losses through building structures

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Signed: Spyridon Karnezis **Date: 17th September 2010**

Abstract:

Simulation of a building when applied early in a design process is capable of reducing significantly its energy consumption. In the first stages however, simulation should provide the user with a broader view of the various design options. Up till now most simulation programs have been created to model final designs with a high level of accuracy. That usually requires numerous specification values especially when CAD models are included before simulations can ever take place. This in many cases might be considerably time consuming and require specialised trained staff.

In order to provide the wider audience with some insight on special weights regarding the many often interactive parameters included, efforts are made to provide means for non technical specialists regarding rapid simulation and early stage energy demand comparison of various building designs. The goal of this thesis has been the creation of such a simplified interface as well as its overview and the exploration of some sample validation cases.

Unfortunately the efforts concerning the calculation of thermal loads which are directly linked to indoor temperature were not fruitful due to time limitations and so the developed tool can only produce results regarding the two nodes introduced in the building shell construction based on a scheduled constantly conditioned indoor temperature at human comfort levels (summer/ winter, occupied / not occupied during the course of a day).

Such a scenario might not be too unrealistic at a time of well insulated newbuilts, when energy saving solutions i.e. mechanical ventilation heat recovery are becoming more and more popular.

Simulations took place regarding the two parameters presented in further detail in this thesis. These are the construction thickness (thermal mass) and the absorbtivity of the outdoor surfaces

Results of the tool have been compared against literature as well as another tool specialised on outer surface temperature calculations from the Lawrence Berkeley National Laboratory.

There is a lot of future work that could be done in order to increase the resolution of this tool, firstly by introducing construction surfaces characteristics i.e. inclination/orientation directly related to incident solar gains and convection heat transfer coefficients. Furthermore the simple model could be enriched by including openings and specifying glazings parameters i.e. U, G- Values related to its location.

1 Table of Contents

2 Introduction

Research has shown that materials covering most of the urban environment in warmer climates i.e. concrete, asphalt etc are primarily responsible for cities to over heat as well as the occurrence of the heat island effect by re-emitting vast amounts of stored heat in the atmosphere during the night. High absorbtivity values of the buildings and streets in combination with a high thermal heat capacity are the main reason making city centres of some countries unbearable during summer. Higher temperatures lead to increasing cooling loads which often are dealt with through power and quantity increase of A/C systems resulting in even worse outdoor conditions especially in afternoon hours of the warmer seasons. This is why energy saving in buildings makes much more sense than subsidising new A/C systems which is sadly currently the case in Greece. Obviously such savings are closely related with the better protection of the structure and numerous alternatives have been introduced of questionable effectiveness and viability (i.e. reflective membranes, complex shading devices, double facades, reflective coatings, green roofs, PCMs etc).

2.1 Context of study/ Rationale:

Why is it important to explore building shell materials and construction elements?

- ✓ The choice of building surface structures based on detailed local climatic data and type of building usage as a mean to maintain moderate indoor temperature conditions in both warm and cold climatic regions is an alternative solution to reduce carbon emissions in the building sector.

- ✓ Findings could help Greek construction companies realize the perspectives of more specialized technical reports/ proposals regarding new shell structures and materials.

- ✓ Such an approach could present a first estimation of the actual loads of a low rise flat roof building, which is the case of most commercial buildings in the Athenian suburbs.

(Greece:Southern European climatic regions have not been researched as thoroughly.)

2.2 The building shell

The “shell” of a building is the total of the transparent and non-transparent structural elements, which determine the exterior outline of the building and separate interior from the exterior spaces. The design of a building shell plays an important role in the thermal energy demand profile of a building and is largely responsible for the shaping of its “indoor climate”. It is via the shell that the building indoor environment is affected. Among others, the following depend on the type, the design and the quality of the shell:

* transmission of heat from and towards the building that is attributed to the horizontal (conduction) and the vertical air movement (convection)

* total thermal losses and gains

* ambient air introduced indoors through infiltration

* solar energy flow in the interior of the building

* thermal-capacity of the building, meaning the ability of the building to store heat in its structures

* ventilation and lighting parameters

* utilisation of renewable sources of energy

* environmental impact of the building structure, both indoors and to the surrounding area

As a result the shell is of outmost importance regarding the thermal and environmental behaviour of the building. In well-insulated buildings, the consumption of energy for heating and cooling is up to 20-40% less than the energy consumption of non-insulated buildings

The energy demand profile of a building depends heavily on its shell characteristics, mainly:

* **orientation** of the building and its position in the plot area. These elements, in combination with the topography of the region, the configuration of exterior spaces and the positioning of neighbouring buildings, determine a line of important parameters of building performance, such as the cooling degree and the solar radiation absorbed (which should be maximised in winter and minimised in summer). Furthermore the wind flow characteristics could be modified in a way as to enhance building natural cooling through ventilation.

* The **form** of the shell (i.e. ratio of transparent to opaque surfaces or total volume to floor area) which determines the thermal behaviour of the building is based on the climatic parameters, as well as the position of the building relative to the neighbouring ones (i.e. buildings with detached walls, present considerably higher thermal losses compared to ones adjacent to each other).

* the **structural elements** of the transparent and non-transparent shell constructions, the attributes determining basic characteristics of structure, such as the heat transfer coefficient regulating thermal losses as a result of convection/ conduction. These elements also determine the absorption coefficient of short wave solar radiation incident on the building, hence the amount of the building solar gains, as well as the building thermal mass.

* the **design of shell openings**, which, in combination with the area's morphology and climatic characteristics, the environment and the building geometry, determines

the existing building ventilation levels as well as the implementation of further cooling and ventilation systems required.

T**hermal comfort** and **environmental indoor quality** (including indoor air quality) is flagged by various parameters. These parameters (air temperature and humidity, surface temperature, wind speed, air renewal, pollutants' concentration) **depend** largely on the **building's shell** characteristics. A very important factor influencing indoor environment quality is the materials' quality used in the coating of shell indoor surfaces.

The use of non-environment friendly materials in the shell production (i.e. materials absorbing largely solar radiation when not needed, cover materials emitting pollutants or harmful particles, high reflectivity transparent surfaces), creates various problems in the environment, such as the intensification of the Urban Heat Island effect (where a metropolitan area is significantly warmer than its surrounding rural areas), air pollution, and glare issues due to reflected solar radiation on the glazings causing visual discomfort to neighbouring building occupants.

In conclusion, the building shell constitutes the most important factor determining the building's thermal and environmental behaviour. The utilization of environment friendly materials and technologies contributes to the reduction of energy needs and in the improvement of conditions indoors and outdoors.

2.3 Thermal mass

The indoor temperature of the building is influenced by outdoor climatic parameters, i.e. solar radiation, ambient temperature, wind speed/ direction and relative humidity as well as indoor thermal gains, i.e. occupancy, lighting, apparatuses and, finally, by the structure's dimensions and the materials' position in it.

The shell of a building may be utilized as **thermal storage**. The structural element in which heat is stored is called thermal mass. Thermal mass is mainly located in walls, ceilings and floors; its size depends on the geometry and the thermal capacity of the materials. An extended thermal mass of a building can beneficially affect it both during summer and winter. During the day all available energy gathered from the increased solar gains is gradually being released inside the building. During winter, the stored heat is released inside the building in the evening or the night, when it is mostly needed. In this way, a part of the thermal needs of the building is covered. Following the same process, in the summer the thermal mass slows down the heat output inside the building during day time. Later the stored heat is gradually released inside the building and towards the outdoor environment, when temperatures are lower.

The **distribution of thermal mass** inside the building is mainly defined by the orientation of the surface, which is exposed to sun radiation and the desirable time delay, regarding heat release.

* on the north-oriented surfaces there is practically no need for any time delay, since these surfaces have small thermal gains

* on the east-oriented surfaces it is preferable to get a time delay of more than 14 hours, so that heat release could happen in the evening

* on south and west-oriented surfaces a time delay of about 8 hours is enough to slow down heat release until the night

* the roof of the building, which is exposed to sun radiation for the greatest part of the day requires an important time delay (therefore, great thermal mass) or, alternatively, some additional insulation.

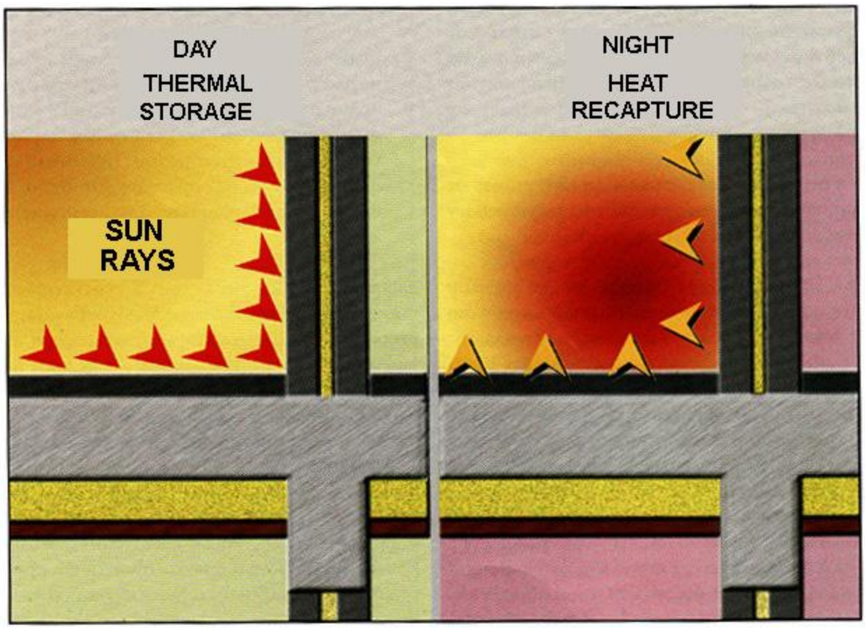


Figure 2.3-1: Function of the floor and walls thermal mass during the day and the night in winter [9]

The larger the thermal mass of the structural elements, the more time is required for their temperature rise and consequently the rise of indoor temperatures.

In this way, not only the highest temperature decreases during the day and, extensively, the cooling load of the building, but maximum shell temperatures are moved on to later cooler hours of the day.

This element is important, since the greatest cooling load doesn't coincide with the greatest demand for energy and so problems (that happen during summer months in hot climates) caused by the overloading of the grid are avoided (in case air conditioning is being used).

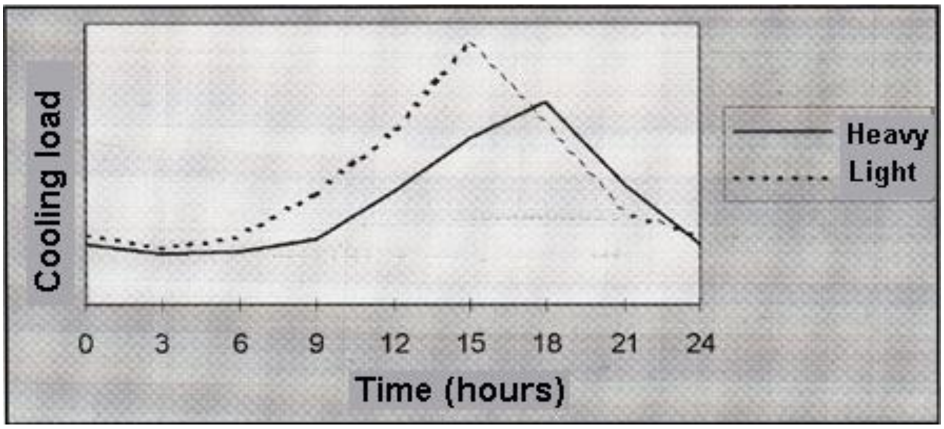


Table 2.3-2: Daily variation of the cooling load for a heavy and a light building [9]

Table 2.3-2 shows the daily fluctuation of the cooling load in a building of small and another of large thermal mass. Early in the morning and at noon, the load is smaller in the “heavy” building with the larger thermal mass, compared to the load of the “light” building with the smaller thermal mass, against the same outdoor load. In the heavy building, the biggest load is smaller than the biggest load of the light building and in addition it is moved to a later time. During the afternoon hours and the night the figures of the cooling load are higher in the heavy building, since the stored heat is partially reemitted indoors. This, however, can be dealt with by the use of natural ventilation, in order to achieve heat removal and the cooling of the shell.

Therefore, thermal mass, combined with the ventilation of the building during the night, plays an important role in the natural ventilation of the building, the decrease of the cooling load and the maintenance of comfortable indoor temperature levels during summer. For these reasons, thermal mass is one of the most important factors regarding passive cooling systems. The utilisation of the building mass for the storage and distribution of excess heat is one of the oldest techniques in the architectural field. A feeling of comfort is created by the indoor spaces of traditional buildings, which are constructed with thick stone or brick walls.

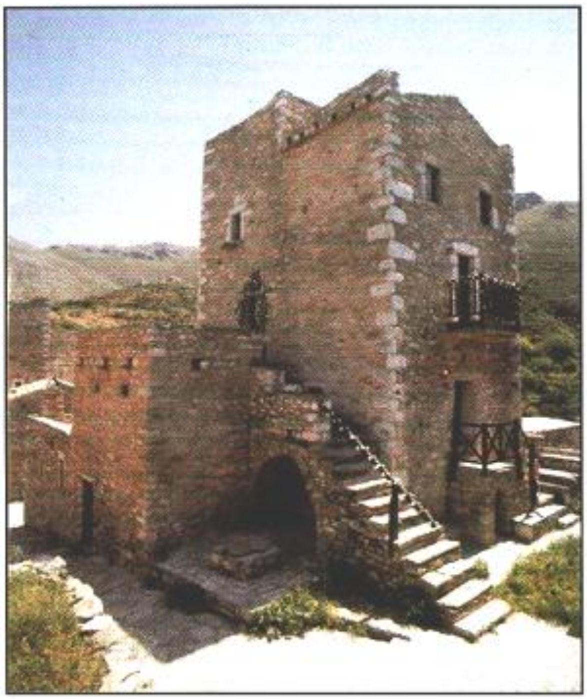


Figure 2.3-3: Traditional building in Mani, Greece, with heavy structural elements and very good thermal behaviour during the summer period [9]

In contemporary buildings, thermal mass consists of elements that are used for the lining of the shell, i.e. bricks (plain or thermally insulated), concrete and concrete blocks. However, it is advisable, wherever possible, to use stone. On the contrary, materials like wood in the shell of the building do not enhance heat storing. As specific heat is the same for almost all the materials used in walls, the heat capacity of a material is analogous to its volume and density. Stone has the greatest density among the materials mentioned above, then the bricks and finally concrete. Therefore, these materials display the greatest thermal capacity and their use is recommended for thermal storing.

An important element that should be taken in consideration by the designer is the relation of the insulation to the thermal mass of the building. It is obvious that in order for a building to take advantage of thermal mass's beneficial qualities, insulation should be always placed on the external part of the building elements used for storing heat. Otherwise, the storing of excessive heat in the building elements or its disposition indoors in a subsequent time isn't possible.

2.3.1 Diurnal heat capacity

The value defining the ability of thermal mass to absorb heat from indoor spaces (i.e. internal solar gains) and reemit it at a later stage (i.e. during night time) is called diurnal heat capacity, defined as the thermal amount stored per degree fluctuation of construction temperature. This amount depends mainly on the characteristics of the material in immediate contact with the indoor air and is the product of heat capacity of the material by its heat conductivity.

Material	5 cm	10 cm	15 cm	20 cm	25 cm
Concrete	120	200	240	245	245
Stone	100	175	185	185	185
Brick	80	140	150	150	150
Wood	30	35	35	35	35

Table 2.3.1-1: Diurnal heat capacity of various materials (KJ/K m^2) [9]

In table 2.3.1-1 values of various materials' diurnal heat capacity relative to thickness are shown. The maximum values are achieved by a combination of external insulation and large internal thermal mass.

As seen on the table, heat capacity stops increasing beyond a specific material thickness, rendering useless any additional increase of thermal mass.

2.3.2 Response Time delay

Another parameter that characterises the behaviour of thermal mass of a structural element is the **response time delay (Δφ)** at which thermal mass starts re emitting heat stored in it. This heat depends on the thickness of the element (X) and thermal diffusivity of the material (a), calculated by the following equation:

$$\Delta\varphi=1,38\ (X/a)^{1/2}$$

2.3.3 Decrement factor

The consideration of thermal mass of the building structure reduces the diurnal temperature flux indoors relative to the ambient, which provoques an increase of temperature in winter during night time and a temperature decrease in summer during daytime. The ratio of the range of diurnal indoor and ambient temperature flux is called **decrement factor**. Its value depends on the wall thickness, thermal diffusivity and the period of temperature flux.

Materials with a low decrement factor are appropriate for the application of techniques for passive heating/cooling, as they contribute to the maintenance of small indoor temperature flux, both in winter and in summer period.

2.3.4 Thermal resistance

Thermal resistance (R) of a material measures the difficulty by which heat is transferred through a material. Thermal resistance depends both on the material thickness, fluids surrounding it (i.e air) and on its thermal conductivity (k). For a compound material, thermal resistance equals the sum of the thermal resistances of its elements.

Thermal conductivity is a characteristic property of every material and it is equal to the heat flow through the mass of the material per unit thickness and temperature difference. Therefore, it is measured in W/m² ºC. Since the relation between thermal resistance and thermal conductivity is expressed by the formula R=k/X (where X is the thickness of the material), it is obvious that thermal resistance is measured in m² ºC/W.

2.3.5 Overall heat transfer coefficient

The opposite of thermal resistance is **the overall heat transfer coefficient** of the material (U-value); it is measured in W/m² ºC and it expresses the way the building exchanges heat with the environment through its shell. As in the case of thermal resistance, the heat transfer coefficient depends on the phenomena of heat transportation that take place in the inner and outer side of the shell and on the thermal properties of the material (thermal conductivity). The relation given by the U-value for a compound building element is the following:

surface heat transfer coefficients relative to radiation and convection conductances

$$R = 1/U = 1/h_i + 1/h_o + \Sigma X_j/k_j$$

$\mathbf{k_j}$: thermal conductivity coefficient of the material

$\mathbf{X_j}$: material thickness

$\mathbf{h_i}$, $\mathbf{h_o}$: indoor and outdoor surface heat transfer coefficients

The successful thermal insulation of a structural element results in the reduction of its heat transfer coefficient (U value), thus in the limitation of heat escape through the element. Table 2.3.5-1 shows average typical values of U for the main structural elements of different kinds of buildings, as well as the values one could now achieve by applying improved heat insulation.

Construction element	Old building	Energy efficient building	Optimum efficiency
External wall	1,4	0,2	0,15
Window	5,2	1,0	0,7
Glazing	5,7	0,7	0,4
Attic	1,0	0,2	0,1
Basement floor	0,8	0,25	0,2

Table 2.3.5-1: Comparing various overall heat transfer coefficients (W/m² ºC) [9]

For the external walls, a value of U equal to 0,15 W/m² ºC is today realistic and it can be achieved with the use of plain bricks as structural elements with external thermal insulation. Constructions using monoblock can have a minimum value of U equal to 0,35 W/m² ºC. For the attic, values of U equal to 0,17 W/m² ºC can be achieved, with a fairly low cost, using polystyrene and insulation of metallic fibres. The insulation of the floors may lead to values of U not greater than 0,2 W/m² ºC. Finally, glass panels with values of U less than 1,2 W/m² ºC are currently available in the market.

The most popular method to limit heat losses is heat insulation, meaning the addition of materials with great heat resistance in the shell of the building, so that overall heat resistance increases. Another way regarding losses from radiation, is the addition of barriers to the heat flow, by putting, for example, aluminium foils behind the thermal sources or by using glass panels with very low capacity of thermal radiation emission.

2.3.6 Thermal insulation on the opaque surfaces

The correct and complete heat insulation in the shell of a building results in:

* better thermal comfort indoors

* decrease in the possibility of vapor condensation on the building surfaces, since it eliminates **thermal bridges**, (the meeting points of the shell elements), which have a high heat transfer coefficient resulting in an intense local heat flow from the building to the environment, due to the abrupt fall of surface temperature. Figure 2.3.6-1 shows some characteristic examples of thermal bridges, due to the wrong placement of the insulation.

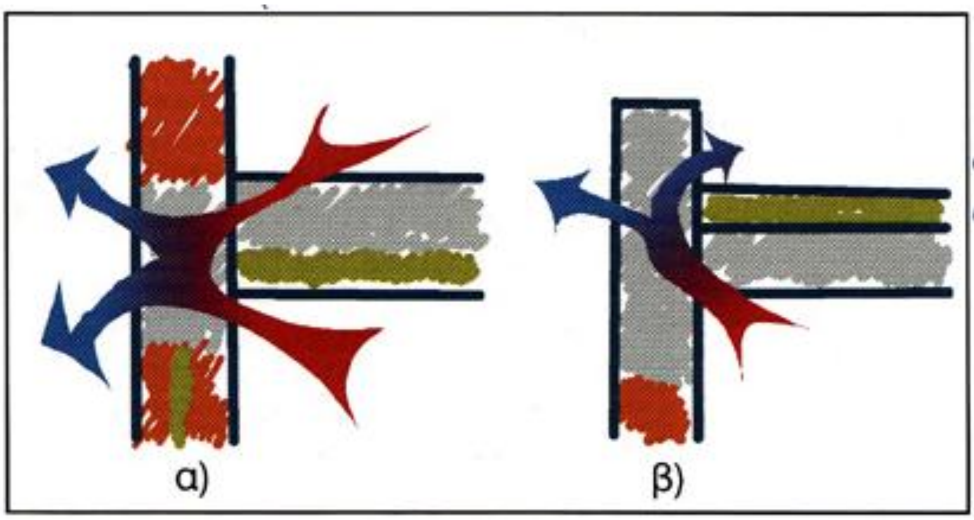


Figure 2.3.6-1: Thermal bridges a) Beam b) Roof [9]

* The increase of building cost, but also the reduction of maintenance costs of the building, achieved by the expected energy saving.

* Thermal solar gains are stored indoors for a longer time period.

The installation of thermal insulation should be made carefully and uniformly, in order to avoid thermal bridges. Furthermore, the choice of the material and its placement (indoors or outdoors) should be assessed in accordance to the heating strategy and the characteristics of the building (functioning hours, thermal mass, solar gains, etc.). Finally, the thickness of the insulating material should be counted considering both energy gains and costs. Energy gains from the installation of thermal insulating material in a structural element are not clearly analogous to the thickness of the insulating layer, since above a specific value of thickness, energy saving is insignificant. This is shown in figure 2.3.6-2 where, by simulation, the outcomes of energy consumption for heating purposes are measured, in accordance to the increase of thickness in the external insulation (a) on a side wall (b) on the roof of a typical building located in Salonica, Greece.

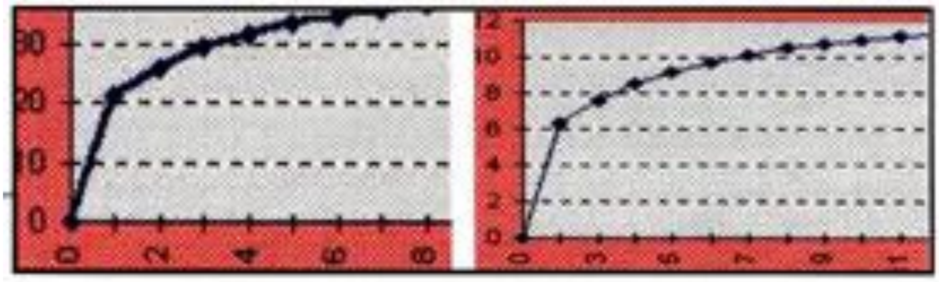


Figure 2.3.6-2: Energy gain due to increase in thickness in the external insulation on a side wall (left) and on the roof (right). Horizontally = the insulation thickness / Vertically = Energy gain in % [9]

The increase of the thermal insulating capacity of the building's shell includes interventions on the external walls, the attic and the floor, when the latter is located next to non heated areas (basement) or outdoors (pilotis) or even to indoor structural elements, which are next to non controlled (free floating) areas (warehouses, closed rooms, etc.). The degree of intervention in thermal insulation of the building very much depends on whether the building is new or retrofitted. According to current heat insulation regulations, new constructions must include the best possible shells. Obviously this is more difficult to achieve in retrofittings.

Based on current trends, the external walls are constructed in two ways:

a) by using **thermal insulating concrete structural materials** (i.e. thermal insulating bricks, thermoblock, monoblock) which are porous materials with low thermal conductivity. The air that is trapped into the great number of cavities inside the material, increases insulation capacity, and the application of additional insulating material becomes useless, especially in Mediterranean climates. However, for further improvement of the material insulating properties, the use of insulating coating is recommended.

b) by using conventional structural materials (i.e. bricks, concrete) and a layer of insulating material (usually extruded or expanded polystyrene, glass wool, insulating material with metallic or herbal fibres, etc.). The wall then consists of an external insulating layer, which obstructs the passage of heat to or from the outdoor environment and of a layer with great thermal capacity, which is used for storing heat (thermal mass). This construction is thinner than the one made with concrete. The external insulation of the side wall:

* eliminates thermal bridges

* increases the building life expectancy by protecting the shell against weather conditions

* takes advantage of the bricks thermal capacity in the application of heating and cooling passive techniques

A variation of this construction often used in Greece, is the installation of the insulation between two layers of material with high thermal capacity (i.e. brick), while in special cases, when the use of the building requires rapid heating or cooling of the internal areas for a limited period of time, (i.e. movie cinemas, churches, etc.) placing the insulation inside the thermal mass is recommended, so that thermal energy is not stored in the walls, but immediately diffused in the area.

Another common variation is that in which there are insulation materials and an air layer between two layers of bricks or other materials with sufficient thermal mass. In this case, in order to get effective thermal insulation, the insulating material should be placed in the external side of the inner wall (figure 2.3.6-3), otherwise it provides almost no protection at all.

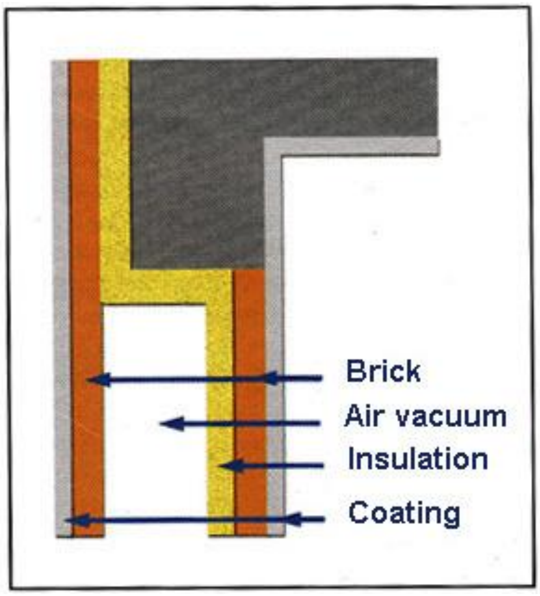


Figure 2.3.6-3: Two-layer insulation with air vacuum [9]

Finally, a very good solution, which is in every case recommended, especially when the climate is humid and warm, is the ventilating facade. In this case, in the air vacuum between the two walls and the insulation, the air may circulate and renew itself, due to the natural air circulation. In this way, the formation of vapors is avoided and during summer, overheating of the shell is also avoided.

Thermal insulation of the attic

The correct thermal insulation of the roof, whether it is an inclined or a flat one, is important for the best energy function of the whole building. The requirements that the roof should satisfy, (especially the flat roof, which is the commonest today) in order to avoid the exhaustion of the building and to best regulate the indoor climatic conditions, can be summarised as follows:

* thermal insulation should be **waterproof**, in order to protect the building from rain and humidity

* it should have the **necessary inclination**, in order to enhance water removal

* it should provide indoors the necessary **thermal protection,** both in winter and summer

The materials commonly used to insulate an attic are different types of extruded polystyrene, glass wool and metallic fibres, while mostly in brick roofs, natural environmental friendly insulating materials can also be used, i.e. recycled paper, cork, cotton and plant fibres, which, however, are rather costly.

In flat roofs, insulation is placed outside the armed concrete, so that thermal mass would be indoors, while the appropriate technique is the use of inverse attic, that is, of a layer of thin concrete or other material (i.e. peddles) which is placed on the ground temperature changes slowly and is usually higher than the outdoor temperature in winter and lower in summer. In warm climates, the lack of floor insulation facilitates the abduction of excessive heat on the ground.

If the floor is in contact with a non-heated area (or pilotis), adding insulation is recommended (especially in the second case), even though the losses are not as important as losses from other structural elements (side walls, attic). The insulating material should be placed in the external side of the floor, so that the heat is stored in the thermal mass. Apart from thermal protection, floor insulation towards the pilotis provides also sound insulation

2.3.7 Window losses reduction

During the last years, technology development in the field of glass panels for windows has moved forward rapidly. Until 2-3 years ago, a glass panel with coefficient U equal to 1,8 W/m² °C was considered best, while today it is common to find glass panels with U values less than 1,2 W/m² °C. Glass panels with coefficient of thermal penetration capacity equal to 0,4 W/m² °C are now available which, however, are placed in frameworks with higher U value. This is why the overall thermal penetration capacity of the element is slightly higher. It is estimated that there will be important improvements in this field in the future, so that glass panels become completely insulated.

Figure 2.3.6-4: Double glazing with wooden frame

Insulated thermal glass panels significantly decrease losses through the shell transparent, allowing the addition of transparent (and larger) structural elements, thus improving natural lighting and solar gains. The most popular types of insulated glass panels (with values of the coefficient of thermal penetration capacity less than 1 W/m² °C) include:

* semi-transparent insulating materials and glass panels with aerogel

* Multiple layer glass panels (double, triple) combined with the use of inert gases (argon, krypton) between glass foils and layers of low emission thermal radiation (Low-e). The combination of increased thickness in the glass panels and the inert gases inside them, leads to very low numbers of the thermal penetration coefficient, comparable to the numbers of non transparent elements. The low emission coefficient special layers allow selective penetration of solar radiation, since they restrict the infrared rays penetration. According to their placement, they are either used to achieve thermal gains indoors in winter or to restrict the passage of infrared radiation indoors in summer.

3 Parameters affecting Building heat gains/ losses

3.1 Solar gains

3.1.1 External Surface orientation/inclination

In order to better protect a building from the sun and utilize its power as best as possible, it is important to consider the orientation and inclination of a building construction surface when designing the openings and the type of construction concerning the opaque elements as well as external surface absorbtivity levels.

Here are some basic equations regarding the sun's orbit around earth which could help us estimate the incident solar energy on the various building surfaces.

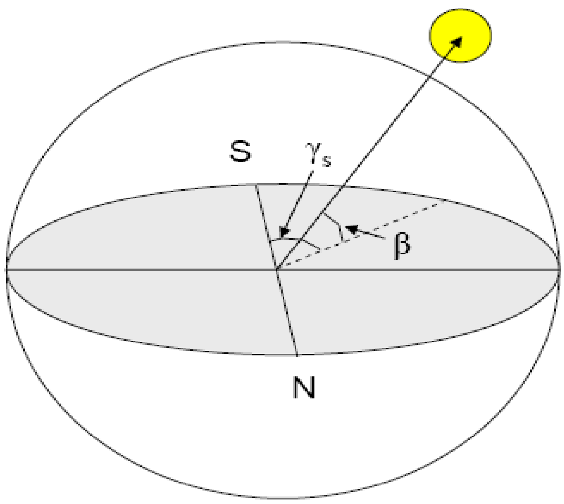


Figure 3.1.1-1: Solar path

Declination: Is the variability of seasonal angle with the 23.5 deg declination angle from normal orbit

$$\delta = \delta_0 \times \sin\left[\frac{360 \times (284 + n)}{365}\right]$$

$n =$ day of the year $\delta_0 = 23.5$

Correction E (mins):

$$E = 9.87 \sin(2B) - 7.35 \cos B - 1.5 \sin B$$
$$B = \frac{360(n-81)}{364}$$

Local solar time (hours) and hour angle:

$$t_{sol} = t_{ref} + \left[\frac{4(L_{ref} - L) + E}{60}\right]$$

$$h = 15 \times [12 - t_{sol}]\ am$$

$$h = 15 \times [t_{sol} - 12]\ pm$$

t sol : solar time regarding the longitude L

tref :unadjusted referenced time

Lref: reference longitude concerning tref =0

NB t: hour fraction

Elevation **β**:

$$\beta = \sin^{-1}\left(\cos l \cos h \cos \delta + \sin l \sin \delta\right)$$

Solar azimuth **γs**:

$$\gamma_s = \cos^{-1}\left(\frac{\sin l \cos h \cos\delta - \cos l \sin\delta}{\cos\beta}\right)$$

Direct solar radiation falling on a surface at a tilted angle Φ:

$$I_{b\Phi} = I_{bV}\cos\Phi + I_{bH}\sin\Phi$$
$$= I_b(\cos\beta\cos\alpha\cos\Phi + \sin\beta\sin\Phi)$$

α= wall solar azimuth which takes into account the surface orientation relative to south: $\alpha = \gamma - \gamma_s$

Diffuse radiation falling on a surface at a tilted angle Φ:

$$I_{d\Phi} = I_{dH}\frac{1+\sin\Phi}{2}$$

3.1.2 Absorbtivity levels & reflective coatings

Improvement of thermal comfort in buildings and the surrounding environment with the use of cool materials

In the centre of Athens, temperatures up to 10° C higher than in suburban areas have been recorded. The adoption of various methods for the control of the urban heat island phenomenon is of imperative necessity for the viability of cities. One of the methods to address this phenomenon and its consequences is the use of cool materials.

In heavily populated urban districts air temperature is higher (by 5º-6º C) than the corresponding temperatures in neighbouring suburban and rural areas. This phenomenon is called "urban heat island" and it represents the characteristic and obvious outcome of urbanisation. The consequences from the phenomenon of urban heat island are serious: thermal discomfort conditions for the habitants, health issues (heat strokes, various organs' dysfunctions, etc.) due to extreme temperature rise, when conditions of burning heat prevail, increased energy consumption for cooling, increase of electricity peak loads, which may lead to electricity distribution problems, when power generating units are unable to satisfy increased demand, increase of energy cost and increase of air pollution and high CO_2 emissions, due to photochemistry. Temperatures up to 10º C higher in comparison to the suburban districts have been recorded in the centre of Athens (Akbari et al, 1992, Oke et al, 1991, Cartalis et al, 2001, M.Santamouris, 2008). Obviously the adoption of methods for the control of urban heat island is of imperative necessity for the cities' viability. One of the methods to address this phenomenon and its consequences is the use of cool materials.

What are cool materials

Cool materials are characterised by high reflectivity towards solar radiation especially near the infrared spectrum. As a result, these materials display lower surface temperatures, in comparison to other materials that don't have these properties. Therefore, less heat will be transmitted from the shell indoors and from the cool surface to the overlying air layers towards the urban environment (Synnefa et al, 2006, Bretz et al, 1997, Berdahl and Bretz, 1997).

Benefits

The various benefits that result from the use of cool materials in the building's shell and in the urban environment can be summarised bellow:

Improvement of heat comfort conditions in buildings that are not air conditioned

Since solar radiation is reflected and it is not absorbed by the shell of the building, less heat enters.

Energy saving for cooling needs and the corresponding financial gain

Lower temperatures indoors result in the limitation of cooling demand. Energy saving for cooling caused by the application of cool materials differs from building to building due to various insulation levels, the construction elements and the function of the building, the air conditioning system and the climatic conditions of the area. Extensive studies show that the application of cool materials in the building shell causes a decrease of the cooling load, which fluctuates from 10 to 40%, while it can reach even higher percentages depending on if:

* it is located in a district characterised by warm climate and sunny weather

* it is poorly or non insulated (i.e. in cases of buildings constructed in old fashioned ways, which represent about 90% of the total number of Greek buildings, ESYE 2006).

* The roof surface of the building is fairly large, compared to its other surfaces

The use of cool materials also results in the reduction of the electricity peak load, hence in money saving, mostly in commercial and industrial buildings, the cost of which doesn't depend exclusively on electricity consumption, but also on the high power demand during the charging period. In addition, due to the decreased load, according to which the size of the air conditioning system is measured, systems of reduced size can be used. Also, the decrease of peak load for cooling contributes to the decrease in power cuts during burning heat periods.

Greater life span for the roof and financial gain by decreased maintenance costs

Cool materials protect the surface on which they have been applied from the devastating ultraviolet solar radiation and the thermal exhaustion. A surface dilates and contracts daily, since it is heated during the day and cooled out during the night. If the surface is covered with some reflective material, temperature fluctuations will be reduced, and thermal exhaustion less, resulting in a longer life span and less maintenance costs.

Facing the heat island phenomenon

The lower surface temperature that cool materials provide, results in the transmission of smaller amounts of heat from the cold surface of the overlying layers to the urban environment. The use of cool materials in an urban scale will result in the decrease of air temperature at an average of 1°-2° C (Synnefa et al.2008, Taha 1997, Taha et al.1999).

Reducing air pollution and of CO^2 emissions

The reduction of air pollution and of CO^2 emissions is due to the decreased pollutant emissions by energy production factories, as needs for cooling are also reduced following the application of cold materials. Furthermore, given that a great percentage of air pollution depends on photochemical reactions, whose speed increases with temperature rise, even a slight decrease of air temperature caused by the application of cold materials, can contribute to air pollution decrease. A probably negative consequence of cold materials use could be a slight energy consumption increase of heating needs during winter, since solar radiation that could contribute to the heating of the building is reflected.

However, during winter the amounts of solar radiation that reach the building are reduced (less daytime duration, smaller sun angle, clouds). Therefore this increase is not so important to override summer energy gains in warm climates with significant sunshine.

Cool material categories

Cool materials are divided in two basic categories:

* materials for the building shell

* materials for the urban environment (asphalt, cement, marble, etc.)

In many areas with warm climate and significant sunshine (i.e. In the Cyclades islands) there are many examples of traditional architecture with light coloured surfaces (roofs, walls, streets) that reduce solar gains.

Today white coloured cold materials have also been developed (Synnefa et al., 2007, Akbari 2004, ABOLIN, BASF) in cases where the use of light coloured surfaces causes glare issues, but also in cases where dark colours are preferred for aesthetic reasons.

The cost of cool materials is generally similar to the cost of conventional materials. Even in cases where cool material cost is increased in relation to the corresponding conventional one, the financial gain from the application of cool materials (which last longer) is more significant.

As far as how these reflective or cool coatings work, their main characteristic is that they have higher reflectivity values in the near infrared solar spectrum which is the main reason why they are very effective in maintaining low temperatures on roof surfaces.

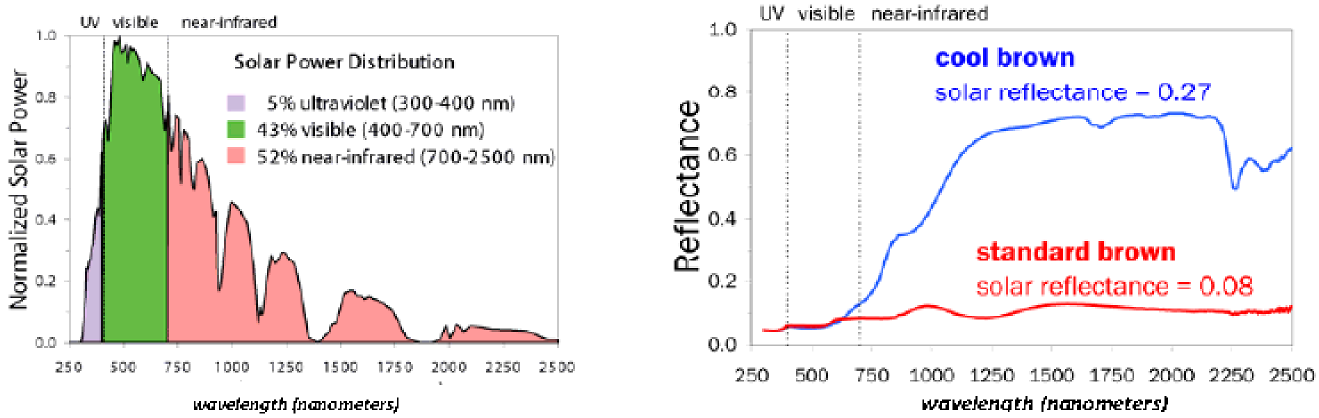


Figure 3.1.2-1: Solar power distribution and a comparison between conventional and cool coatings of the same colour

[7]

Research has shown that at peak solar conditions of 1000W/m^2 in the case of an insulated surface with a solar absorbtivity of 0.95 is approximately 50 deg C higher than ambient temperature in case of low winds. In case of a white surface with an absorbtivity of 0.2 the temperature rise is around 10 deg C. Measurements prove that a cool coating may reduce a concrete tile's temperature by 7.5 deg C. Colored coatings highly reflective in the near infrared are also being developed in case darker colours are required (8).

3.2 Conduction convection radiation summarised values

The following table provides some typical conductance values by which the indoor and outdoor heat transfer coefficients can be estimated. In the case of still air (i.e. indoor heat transfer) convective and radiative heat transfer coefficients have values of the same magnitude order. Thus emissivity is quite important affecting in addition surface conductance.

When wind speed exceeds certain values, usually over 4 m/s convection becomes much more important.

Orientation	Air Velocity m/s	Direction of heat flow	Surface emissivity		
			0.9	0.7	0.5
Horizontal	still	up	9.4	5.2	4.4
Horizontal	still	down	6.3	2.2	1.3
Vertical	still	horizontal	8.5	4.3	3.5
any position	3.7	any	23.3	-	-
any position	6.4	any	35	-	-

Figure 3.2 -1: Conductance W/m2K for various orientations, wind speed, surface emissivity (C. Arora)

The rate of heat transfer under steady state conditions can be written in terms of indoor/outdoor temperatures combined with the overall heat transfer coefficient:

$$q_{in} = U(T_o - T_i) = \frac{(T_o - T_i)}{R_{tot}} \quad W/m^2$$

U overall heat transfer coefficient

Rtot total heat transfer resistance

Bearing in mind the afore mentioned heat transfer network the above could be otherwise written:

$$\left(\frac{1}{U}\right) = \left(\frac{1}{h_i} + \frac{\Delta x}{k_w} + \frac{1}{h_o}\right) = R_{tot} \qquad (W/m^2.K)$$

Δx: thickness

Kw: thermal conductivity

In the case of a building the general equation would have a form similar to the following:

$$U_o = (U_{wall} \cdot A_{wall} + U_{door} \cdot A_{door} + U_{window} \cdot A_{window} \ldots) / A_{total}$$

Where Uwall, Udoor, Uwindow, Awall, Adoor, Awindow, Atot the overall heat transfer coefficients and surface areas of wall, door, window and total respectively. The above equation is valid when temperature differences across structure elements are the same and heat transfer flows are parallel.

3.3 Ventilation

Ventilation and infiltration are two highly complex issues which were not further researched for this project.

We have however introduced varying air change per hour values depending on time of day (natural night cooling i.e. summer) representing both infiltration rate and ventilation in case the developed tool of chapter 5 were to be developed further and make estimations of indoor free floating temperature conditions.

$$Q_{v/inf} = \Delta V_{air} * \rho_{air} * C_{air} * (T_{amb} - T_i)/3600$$

$Q_{v/inf}$: heat gains/ losses due to fresh air replacing partially indoor with specified rate (kWh)

ΔV_{air}: air volume rate (ach)

3.4 Internal gains

By internal gains are meant thermal gains related to sensible heat from operating equipment and occupants and can be roughly modelled based on seasonal domestic heat gain statistical data.

We can presume average daily values as shown in the following table [21]:

domestic seasonal heat gains		
	33 weeks-100m2 (MJ)	*daily averaged-100 m2 (MJ)*
Q_{ocp}: *Body heat (3 person)*	3000	14
Q_{cook}: *Cooking (electric)*	3500	16
Q_{dhw}: *Water heating*	2000	9
Q_{el}: *Electricity incl. lights*	3000	14
Sum		53

Table 3.4-1

The above sum is equivalent to 54 kWh/m2/Year. Summer values due to less lighting, water heating requirements etc have been reduced by 30% compared to seasonal which are represented by the 33 week values published as 'seasonal' thermal gains.

Weight factors have been applied based on weeks with each consumption scenario.

The daily averaged heat gain for our A_{floor} (m2) model is

Qx /day=((seasonal total amount)/(33weeks*7days)*(33/52)+0.7*(seasonal total amount)/(19weeks*7days)*(19/52))*(A_{floor} m2/100 m2)*10^6

X= ocp, cook, dhw, el

Simple scenario that can be modified and can be introduced in the tool is developed in the 5^{th} chapter in case of cooling / heating load calculations:

From 00:00 till 16:00 was considered that people are asleep/ away and very roughly little energy is consumed approximated by maintaining the occupancy thermal gains throughout the period. This would mean that half the daily occupancy heat emitted is divided by 16 (hours) and considered for each hour. From 16:00- 00:00 we have included the rest of the loads divided by the hours available to come up with the hourly emissions.

The floor area of 100 m2 has been converted to our model's A_{floor} m2.

Qe = IF(t0<16;Qocp/32;Qocp /16+(Q cook +Q dhw + Q el)/8)

4 Calculation methods

When there is a temperature difference between conditioned indoor area and outdoors, heat is transferred through the building shell. If heat is entering the building this is considered a gain or otherwise a heat loss. Fabric heat transfer introduces sensible heat transfer through the whole structure surface area of a building apart from fenestration.

Detailed analysis of building structure heat transfer is quite complex and has to consider the following:

- Complex geometrical structures i.e. walls, roofs, floors, ceilings consisting of numerous materials with various thermophysical properties.
- Ambient climatic conditions varying constantly.
- Indoor conditions varying relative to building type of use, equipment - occupancy schedules, load patterns and naturally outdoor climatic conditions.

Usually for simplification reasons when cooling/ heating loads are calculated, indoor conditions are assumed to be constant. Outdoor weather conditions however need to be considered in order to come up with a realistic cooling/heating load estimation especially when the annual, seasonal and daily swing are of considerable magnitude.

Specifically, in colder climatic conditions, ambient temperature swing during winter is relatively insignificant. Solar radiation values are considered low as well as temperature fluctuation, which lead to heating loads being calculated by a steady state heat transfer equations. This calculation method leads to an overestimation of the required heating capacity. For higher accuracy, it is important to introduce transient heat transfer also during winter time.

4.1 Steady state heat transfer through a building wall (one dimension)

In the case of steady state heat transfer indoor and outdoor climatic conditions are considered to be constant. One dimension is an acceptable simplification when the wall thickness is relatively small when compared to the other two dimensions. Generally all building constructions have multiple layers which are not homogeneous and thus non isotropic. In our case we shall focus on a single layered homogeneous wall construction.

4.2 The homogeneous wall

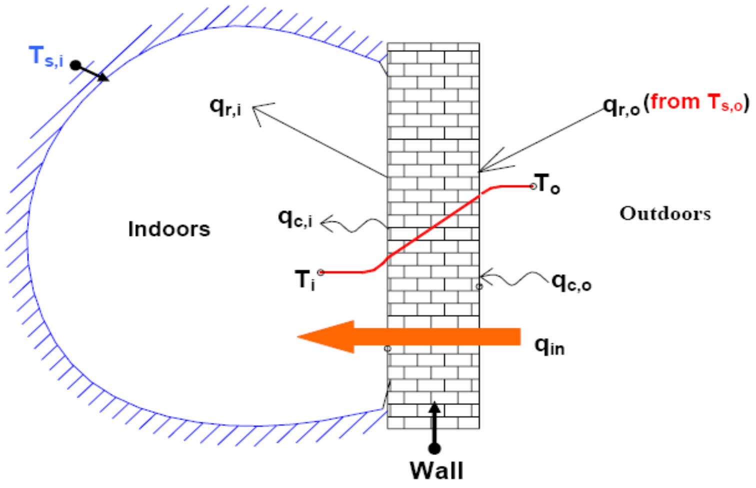
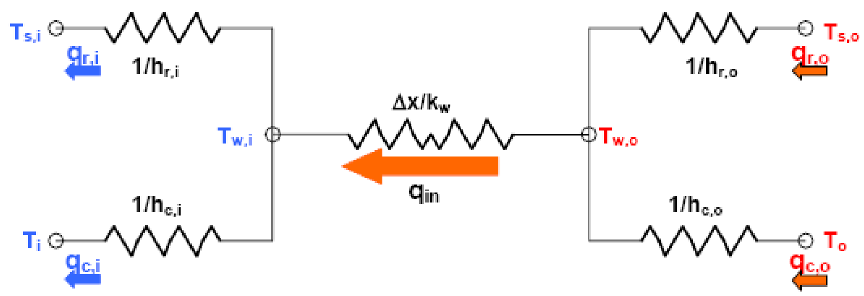


Figure 4.2-1: Homogeneous wall separating a conditioned indoor space from the outdoor environment

In the above Figure 4.2-1 a homogeneous wall separates a conditioned indoor space from the outdoor environment. The wall is exposed to radiation and convection thermal heat transfer on both inner and outer surfaces and to conduction through the wall.

In the case of climatic outdoor and indoor conditions remaining constant, a heat transfer network can be constructed which would consider various heat transfer resistances as shown in the following schematics.



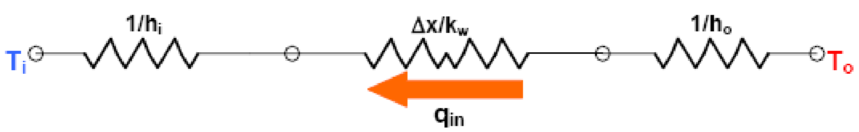


Figure 4.2-2: Heat transfer network considering various heat transfer resistances

The wall heat transfer rate in such a steady state is provided by the following equation:

$$q_{in} = \{q_{c,o} + q_{r,o}\} = \{q_{c,i} + q_{r,i}\} \quad W/m^2$$

$q_{c,o}$ and **$q_{r,o}$**: convective and radiative heat transfers on outdoor wall surface

$q_{c,i}$ and **$q_{r,i}$**: convective and radiative heat transfers on indoor wall surface

In terms of a heat transfer coefficient which is linearised, the heat transfer rate could be written as:

$$q_{in} = h_o(T_o - T_{w,o}) = h_i(T_{w,i} - T_i) \quad W/m^2$$

T_i , **T_o**: indoor and outdoor air temperatures

T_{wi} , **T_{wo}**: indoor and outdoor wall surface temperatures

h_i , **h_o**: indoor and outdoor heat transfer coefficients or surface conductances considering both convection-radiation heat transfers.

The resistance net work easily provides us with the following equations:

$$h_i = h_{c,i} + h_{r,i}\left(\frac{T_{w,i} - T_{s,i}}{T_{w,i} - T_i}\right) \qquad h_o = h_{c,o} + h_{r,o}\left(\frac{T_{s,o} - T_{w,o}}{T_o - T_{w,o}}\right)$$

temperature

4.3 Multilayered walls

In reality building constructions are a combination of materials /air gaps with different thicknesses, properties and inner /outer surface temperatures and conductances not always homogeneous. In such cases a multi layered construction’s rate of heat transfer per surface area can be calculated by the following equations:

$$q_{in} = U(T_o - T_i) = \frac{(T_o - T_i)}{R_{tot}} \quad W/m^2$$

U: overall heat transfer coefficient calculated by:

$$\left(\frac{1}{U}\right) = R_{tot} = \left(\frac{1}{h_i}\right) + \sum_{i=1}^{N}\left(\frac{\Delta x_i}{k_{w,i}}\right) + \sum_{j=1}^{M}\left(\frac{1}{C_j}\right) + \left(\frac{1}{h_o}\right)$$

It should be noted that above equations are referring to plane constructions. In case of curved surfaces construction contour should be considered when estimating heat transfer rates.

4.4 Unsteady heat transfer through opaque constructions

Generally speaking heat transfer through construction elements is far from steady. This is more evident in summer when the combination of ambient temperatures with the solar parameter maintains higher values through the day increasing the diurnal deviation of constructions' temperatures.

When estimating unsteady state heat transfer, thermal capacity of the construction becomes very important. Because of the finite and occasionally large capacity of buildings' constructions, heat transfer rates entering the outdoor surfaces are often quite different from the ones leaving the indoor surfaces.

Specifically if the construction capacity is not significant (i.e. a door between indoor zones), heat transfer shall remain transient in the case of unsteady outdoor conditions. In this case the rate of heat transfer on the outer surface is roughly the same with the inner as thermal storage is neglected.

Furthermore a construction's thermal capacity is responsible for a certain time lag. In the case of a construction having sufficient thermal capacity the unsteady state problem is of a relatively complex nature. One dimensional solutions are considered adequate for general calculations but the simple resistance network described above cannot be used further.

4.4.1 One-dimensional, unsteady heat transfer through building constructions

In this thesis we are focusing on a homogeneous construction made out of one material. The temperature of the conditioned space is considered to be conditioned at a constant temperature. The following figure illustrates a wall in the case of unsteady heat transfer. The construction outer surface is absorbing direct and diffuse solar radiation and is re emitting energy outdoors but also indoors through the inner surface. In addition heat is transferred between the ambient air and the construction's outer surface through convection as is the case of the inner surface with indoors.

The equation describing the thermal heat transfers on the outer surface of a construction (x=L) for any time interval θ is the following:

$$q_{x=L,\theta} = -k_w \left(\frac{\partial T}{\partial x} \right)_{x=L,\theta} = h_o (T_o - T_{x=L}) + \alpha_D I_D + \alpha_d I_d - R$$

The relative equation for the inner surface (x=0) would be:

$$q_{x=0,\theta} = -k_w \left(\frac{\partial T}{\partial x} \right)_{x=0,\theta} = h_i (T_{x=0} - T_i)$$

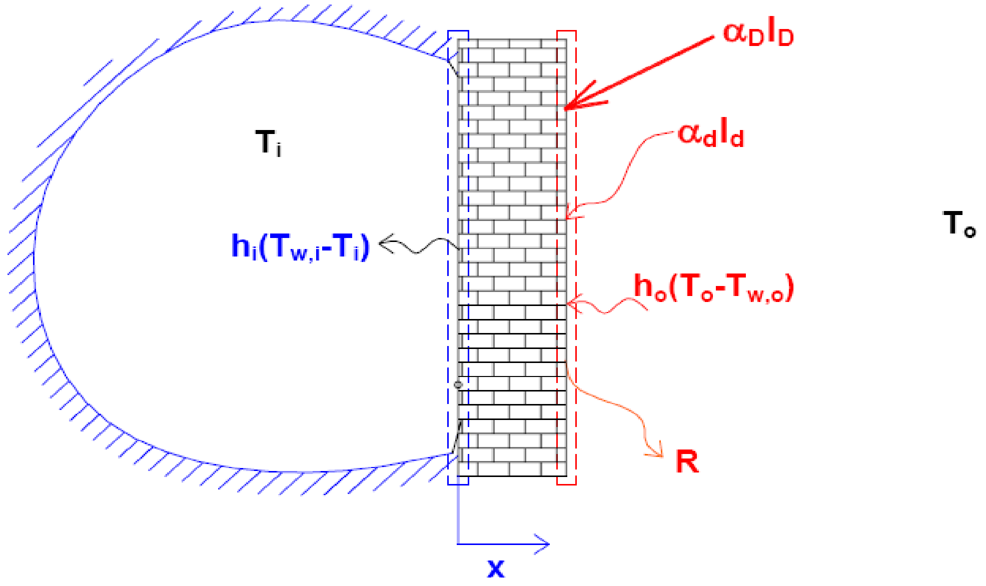


Figure 4.4.1-1: Unsteady state heat transfer through a building construction element

When estimating cooling load, heat transfer rate indoors through the construction ($q_{x=0,\theta}$) is required based on indoor conditioned temperature and inner construction surface temperature for a specific time θ. In calculating $q_{x=0,\theta}$ the construction temperature distribution is required **(∂T/∂x)** from where $\mathbf{(\partial T/\partial x)_{x=0,\theta}}$ is derived and qin. This can be calculated considering only conduction is taking place through the construction for one dimension from the transient heat conduction equation following:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\left(\frac{\partial T}{\partial \theta}\right)$$

Where α: thermal diffusivity ($\alpha = \mathbf{k_w}/\rho_w \mathbf{c_{pw}}$), θ is the time interval and x is the length. The solution of the partial differential equation requires two boundary conditions and an initial specified. Initial condition could be a gradient at a specified time taken to be the starting point in time θ=0.

$$T_{x,\theta=0} = T_i(x)$$

The boundary conditions at x=0,L would be based on equations above i.e. for x=L:

$$q_{x=L,\theta} = -k_w\left(\frac{\partial T}{\partial x}\right)_{x=L,\theta} = h_o(T_o - T_{x=L}) + \alpha_D I_D + \alpha_d I_d - R = h_o(T_{sol-air} - T_{x=L})$$

$T_{sol\text{-}air}$: sol air temperature equivalent to a temperature which would combine the effects of outdoor ambient temperature and radiation energy gains. Obviously sol air as ambient air varies with time in a periodic manner.

Based on the above definition the boundary condition at x=L can be written:

$$q_{x=L,\theta} = -k_w \left(\frac{\partial T}{\partial x}\right)_{x=L,\theta} = h_o \left(T_{sol-air} - T_{x=L}\right)$$

The above equation is possible to be solved through analytical methods (infinite harmonic series), numerical techniques (finite difference/finite volume methods), or semi empirical methods.

4.4.2 Analytical solution

Such solutions can be found regarding simple geometries. An additional simplification is the fact that solar radiation and ambient temperature are considered to be periodic. In case of a country where sun is available 300 days per annum considering a clear sky is an acceptable simplification which could be made in order to support the assumption of ambient temperature and solar radiation to be periodic. Furthermore in such a solution, indoor temperature and thermal properties of the materials are considered to be constant.

If in this case we apply a periodic boundary condition at the external surface, an analytical solution may be taken in terms of an infinite Fourier series which is consisted by various harmonics.

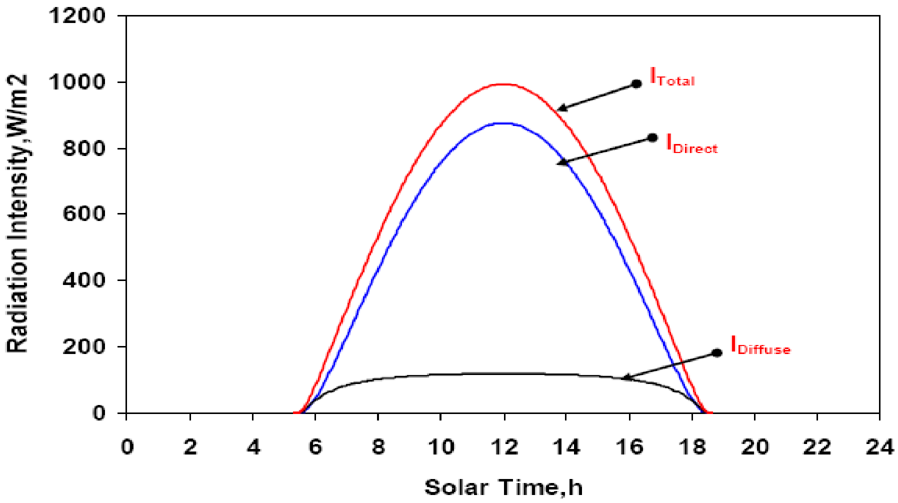


Figure 4.4.2-1:: diffuse, direct, total solar radiation on horizontal surface (clear sky)

Sol air temperature is provided by (Threlkeld):

$$T_{sol-air,\theta} = T_{sol-air,m} + M_1 \cos\varpi_1\theta + N_1 \sin\varpi_1\theta + M_2 \cos\varpi_2\theta + N_2 \sin\varpi_2\theta + ...$$

Mean sol air temperature Tsol air,m is found from the average of the sol air temperature for 24 hours by integration:

$$T_{sol-air,m} = \frac{1}{24}\int_0^{24} T_{sol-air}\, d\theta$$

Where the coefficients are:

$$M_n = \frac{1}{12}\int_0^{24} T_{sol-air} \cos \varpi_n\theta \, d\theta$$

$$N_n = \frac{1}{12}\int_0^{24} T_{sol-air} \sin \varpi_n\theta \, d\theta$$

n : is usually not more than a value of 3 due to higher values contributing insignificantly.

ω_n : angular velocity, **$\omega_1 = \pi/2$ rad/hr or 15^o /hr , ω_n = n ω_1**.

Coefficients are M1M2 & N1,N2 are calculated by the above equations.

By the above equations, sol air temperature can be estimated for clear days in any location. From the above series regarding sol air temperature and the solution of the unsteady heat conduction yields an expression for construction temperature relative to x, θ:

$$T_{x,\theta} = A + Bx + \sum_{n=1}^{\infty}(C_n \cos P_n.mx + D_n \ \sin P_n.mx).e^{(-m^2\varpi_n\theta)}$$

A, B, C, D: constants, $m = \sqrt[4]{-1}$. A, B, Cn, Dn may be real or complex.

In the solution the real parts are taken under consideration. Inner construction temperature is the following:

$$T_{x=0,\theta} = T_{x=0,0} + \frac{1}{h_i}\begin{bmatrix} U(T_{e,m} - T_{x=0,0}) + V_1 T_{e,1}\cos(\varpi_1\theta - \psi_1 - \phi_1) + \\ V_2 T_{e,2}\cos(\varpi_2\theta - \psi_2 - \phi_2)\ldots \end{bmatrix}$$

Te stands for Tsol air

$$U = \frac{1}{\frac{1}{h_i} + \frac{L}{k_w} + \frac{1}{h_o}}$$

$$V_n = \frac{h_i h_o}{\sigma_n k_w \sqrt{{Y_n}^2 + {Z_n}^2}}$$

$$\sigma_n = \sqrt{\frac{\varpi_n}{2\alpha_w}} \quad \& \quad \alpha_w = \frac{k_w}{\rho_w c_{p,w}}$$

Yn , Zn are relative to hi, ho, L, Kw, σn

φn is the time lag

$$\phi_n = \tan^{-1}\left(\frac{Z_n}{Y_n}\right)$$

Heat transfer rate in the internal surface is also in an infinite series form:

$$q_{x=0,\theta} = U\{[T_{e,m} + \lambda_1 T_{e,1}\cos(\varpi_1\theta - \psi_1 - \phi_1) + \lambda_2 T_{e,2}\cos(\varpi_2\theta - \psi_2 - \phi_2)] - T_{x=0,0}\}$$

λn: is the decrement factor

ψn: considers both internal and external heat transfer coefficients, thermal properties of the construction and thickness. The above are related as following:

$$\lambda_n = \frac{V_n}{U} \qquad \psi_n = \tan^{-1}\left(\frac{N_n}{M_n}\right)$$

4.4.3 Numerical methods

The above method although very precise, is also very complex for other boundary conditions or geometries. Numerical methods are power full in solving unsteady conduction equations with nearly any boundaries, properties or shapes. However a power full computer and special attention are required as the solutions are not exact and might deliver errors. These however are the most flexible and versatile methods. Some such methods are the finite difference method, the finite element method, finite volume method etc. The general principal is discretisation of continuous functions.

4.4.4 Semi-empirical methods

These methods use the form of the analytical methods combined with figures derived from experimental data. The problem is that empirical data are available only for standard construction elements, locations and orientations.

5 Excel Tool developed

Nomenclature

introduced values /units		
absorbtivity (outdoor surface)	α	0.3
width (m)	w	10
length (m)	l	10
height (m)	h	3
model volume (m3)	V	300
wall-roof surf area (m2)	A	220

floor surf (m2)	A_f	100
Atot total surf (m2)	A_{tot}	320
overall heat transfer coefficient U-value (W/m2K)	U=1/R	2.05
density [kg/m³] [15]	ρ (conc)	2000
concrete spec heat [J/kg/K]	C (conc)	840
concrete therm conductivity [W/m/K]	K (conc)	1.3
total wall therm resistance [m²K/W]	R_w	0.487
structure volume (m3)	V (conc)	64
Internal surface convection coefficient, W/m²K Default from NFRC-100-iso15059	h_i	4
external surface convection coefficient, W/m²K Default from NFRC-100-iso15060 ashrae	h_o	12
speciffic heat of moist air at 300K (J/kg K) [16]	C (air)	1005
density of moist air kg/m3 [16]	ρ (air)	1.177
thermal gains from body heat (3 person)	Q_{ocp}	3000
thermal gains from Cooking (electric)	Q_{cook}	3500
thermal gains from domestic water heating	Q_{dhw}	2000
thermal gains from Electricity including lights	Q_{el}	3000
Stefan Boltzman constant (W/m2K4)	σ	0.0
surface emissivity longwave for white	ε surf	0.92
thickness X [m] of construction element	X, X_o, X_i	0.1
Biot number (W/m2degC)	β_i	-
Biot number (W/m2degC)	β_o	-
max time step (hr)	dt max	-

5.1 Box model description

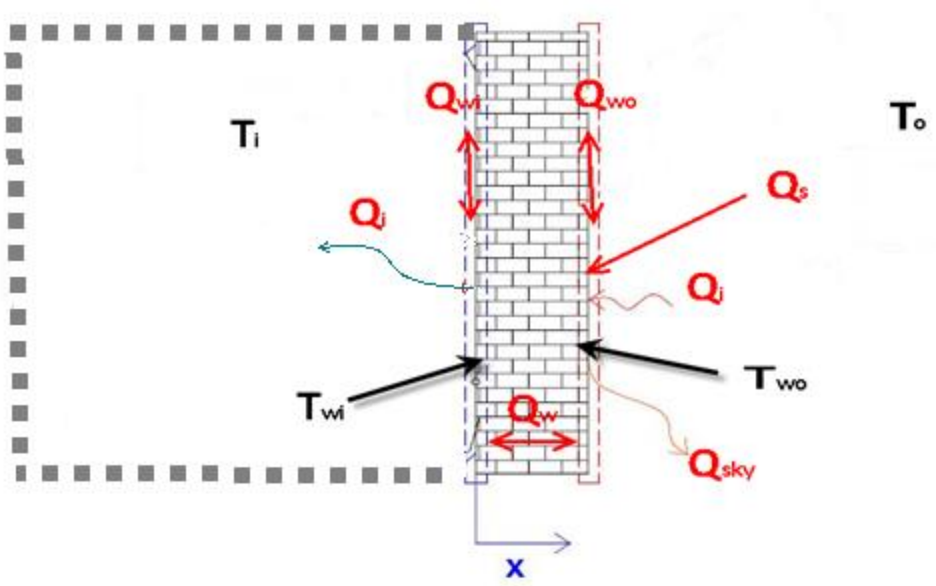


Figure 5.5-1: New built construction exposed to climatic data with variable dimensions

The designed model is basically a homogeneous box with variable dimensions and outdoor surface absorbtivity values. This box is a rough approximation of a new built construction exposed to the climatic data introduced (in this case a southern European climatic data file). It maintains constant indoor temperature values relative to time of day and day of year for a household occupancy schedule through an HVAC system which is not based on some specific regulation. The main concept has been for it to be as simple but realistic as possible and easily varied to provide the user with some introductory understanding of the effect of certain parameters concerning a building shell temperature fluctuation.

The scope of the development of this model was to maintain it simple and sensitive to thermal storage. We could build upon it in the future, introducing various more complex construction elements with a range of orientations and inclinations detectable eventually by an improved successor.

5.2 Equations describing the model

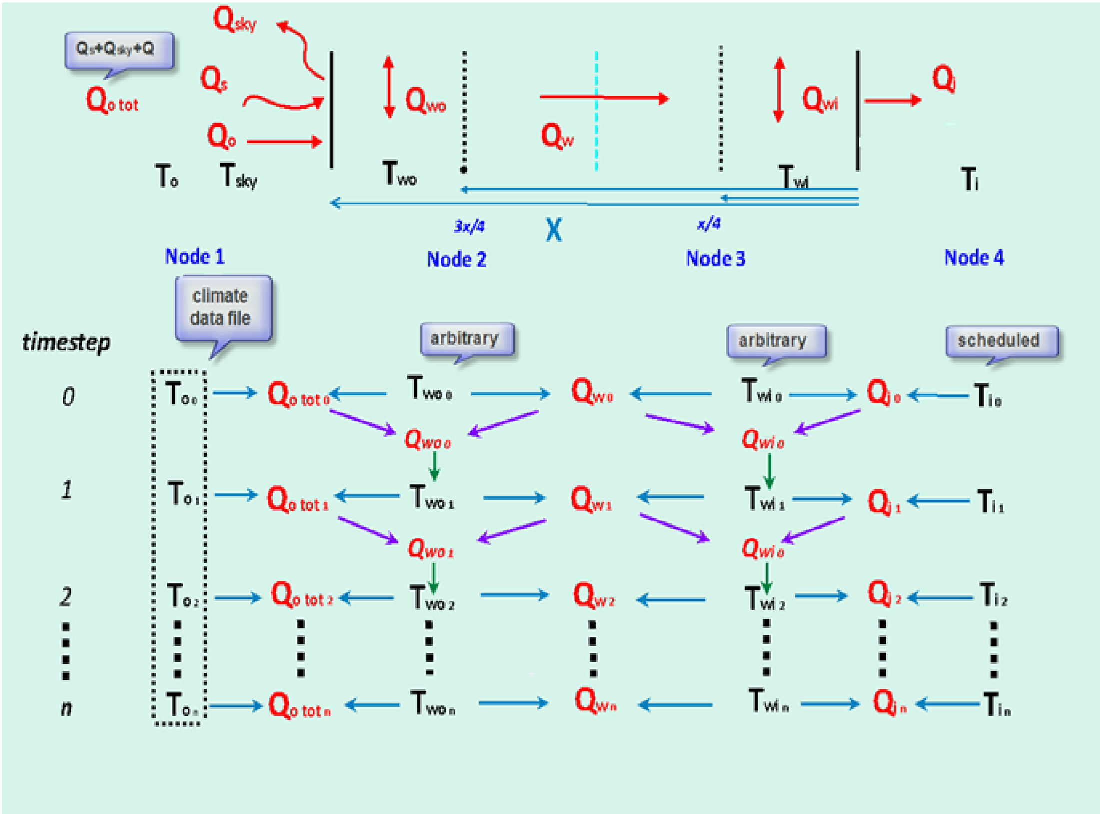


Figure 5.2-1: Time step node temperatures through steady state equations

The basic idea illustrated in the above schematic is that, provided outdoor climatic data are accessible and indoor temperatures are strictly conditioned (based on an annual schedule through an HVAC or even a MVHR system for heat recovery in a new built household), it would be possible to introduce some initial arbitrary values regarding the shell construction (modelled by two nodes in its core) to estimate the following time step node temperatures through steady state equations (these should provide adequately realistic results for an hour time interval). The calculated values could be then introduced to the same pack of equations and lead to the calculations of the next time step values and so forth.

Introducing these equations, arbitrary initial temperature values and climatic data to an excel sheet, could lead to the calculation of a weekly, monthly or even annual estimate of a construction element’s temperature fluctuation.

Specifically, introducing the model calculations in further detail we would begin with the fact that the whole mass of the construction is divided between the external and internal node surfaces.

External construction temperature

Each structure node is considered to contain consequently half the thermal mass of the construction (m_{conc} = ρ_{conc}*V_{conc} = ρ_{conc}* X/2 *A). In this case the thermal balance equation drawn from the summation of heat transfer from convection – conduction between the external surface and outdoor environment Q_{o0} , solar gains Q_{s0}, energy emitted to the sky from the roof Q_{sky0} (heat emitted and absorbed between vertical surfaces and the neighbouring environment is considered to be insignificant) and energy transferred to the construction's core through conduction Q_{w0} should be directly analogue to the temperature increase or decrease of the specific node defined as the thermal energy stored in the external wall Q_{wo0} for a chosen time step i.e $t_0=0$

$$Q_{sky0}+Q_{s0}+Q_{o0}+Q_{w0} = Q_{wo0}$$

(Q is a positive value when heat is transferred from the external to internal nodes where ambient temperature is considered to be the fist temperature node and indoor temperature the fourth as illustrated in the above schematic).

Following are the equations describing the heat transfers occurring on the external construction layer node:

*As shown in the above schematic, the initial heat transfer through convection-conduction derives out of the difference of the ambient temperature T_{amb0} and the external construction node arbitrary initial value T_{wo0} multiplied by a combined conduction-convection heat transfer coefficient relative to the nodes position in the construction (X_o=X/4).

$$Q_{o0} = 1/(1/h_o+(X/4)/k_{conc})*A*(T_{amb0}-T_{wo0})$$

*Heat absorbed in an hour time step interval based on beginning T_{wo0} and ending T_{wo1} construction temperatures is described by the following equation:

$$Q_{wo0} = \rho_{conc} * C_{conc} * V_{conc} * (T_{wo1} - T_{wo0})/3600$$

(we divide by 3600 to convert Joules to kWhrs to maintain same units)

From the above equation regarding the external construction layer node it is possible to calculate from initial arbitrary values, thermal heat transfer equations and climatic data the next time step external construction layer Temperature T_{wo1}.

*Furthermore heat transferred through the construction, since there is no thermal mass considered between the two core nodes, is calculated based on the following simple equation:

$$Q_w = A * K_{conc}/(X/2) * (T_{wo} - T_{wi})$$

*Solar gains have been roughly estimated through the sum of diffuse and normal direct solar radiation from the following equation:

$$Qs = \alpha * A * (I_d + I_D)$$

I_d : solar diffuse radiation (Watts)

I_D : solar direct normal radiation to a surface vertical to the beam direction (Watts)

*Finally heat emitted to the sky from the roof is based on the dew point temperature T_d, construction and sky emissivity values ε_{surf}, ε_{sky} respectively and relative humidity $r.h.$ which have been derived by the following equations:

$$T_d = T_{amb} - (100 - r.h.)/5 \qquad [17]$$

$$\varepsilon_{sky} = 0.006 * T_d + 0.74 \qquad [18]$$

$$Q_{sky} = \sigma * A_f * \varepsilon_{surf} * (\varepsilon_{sky} * (T_{amb} + 273)^4 - (T_{wo} + 273)^4) \qquad [19]$$

Internal construction temperature

In a similar way the internal construction node temperature T_{wi0} is to be estimated through the summation of the energy transferred through conduction from the external node Q_{w0} and heat transferred relative to convection Q_{i0} due to the temperature difference between indoor air T_{i0} and T_{wi0}.

$$Q_{i0} + Q_{w0} = Q_{wi0}$$

Following are the equations describing the heat transfers occurring on the internal construction layer node:

*Heat absorbed in an hour time step interval based on beginning T_{wi0} and ending T_{wi1} construction temperatures

$$Q_{wi0} = \rho_{conc} * C_{conc} * V_{conc} * (T_{wi1} - T_{wi0})/3600$$

(we divide by 3600 to convert Joules to kWhrs to maintain same units)

From the above equation regarding the internal construction layer node it is possible to calculate from initial arbitrary values, thermal heat transfer equations and indoor conditioned constant temperature values T_{i0} the next time step internal construction layer Temperature T_{wi1}.

*Heat transferred through convection - conduction Q_i from the internal construction surface indoors in the case of conditioned constant indoor temperature values is similar to Q_o only the convection heat transfer coefficient maintains a smaller value as air indoors is considered to be still.

$$Q_{i0} = 1/(1/h_i + (X/4)/k_{conc}) * A * (T_{wi0} - T_{i0})$$

5.3 Tool interface

Illustrated below is the tool’s interface where the user is able to introduce values concerning the building geometry , the outdoor surface absorbtivity and has a choice of materials apart from the default concrete values introduced in the 'materials data' sheet. The user can introduce his/her own hourly data in the 'climate data input' sheet and work on a different climatic region.

When changing a value on the 'tool interface' sheet excel automatically re-calculates all parameters interrelated and the results are illustrated graphically for a year, a winter and summer month - week in order to observe at different resolutions the effect of a certain parameter.

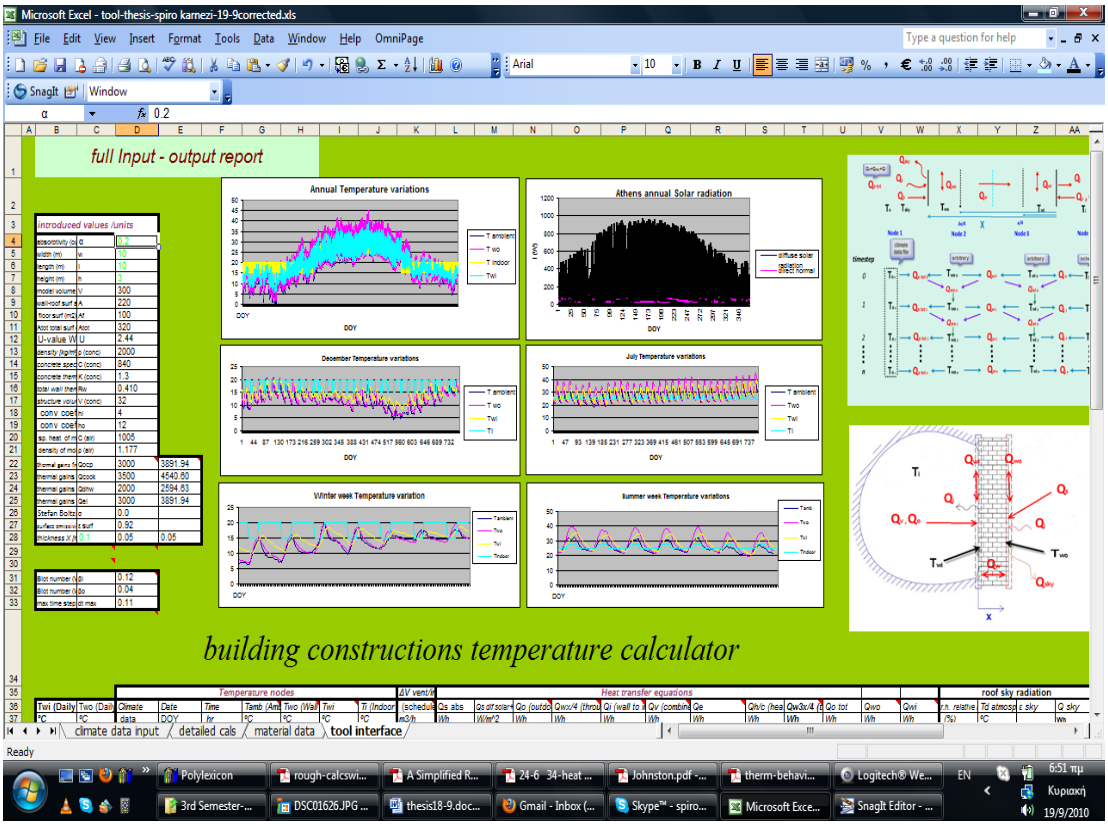


Figure 5.3-1

In this tool on the left hand side of its interface are roughly 20 parameters that can be varied and which are linked to more than 20 equations illustrated at the bottom of the sheet. These equations are applied in an annual climatic data file with an hourly time step and the graphs are presented in order to support the understanding and help interpret the results.

There has been some further work done in this tool in order to be prepared in a later stage to estimate free floating indoor temperatures and heating and cooling load requirements estimates considering varying ventilation-infiltration rates and equipment- occupancy internal thermal heat gains.

6 Results

Concluding from the literature review, heat is anticipated to be stored in a building's structure and partially delivered indoors at a later time.

This could be proven to be quite beneficial in terms of reducing peak heating and cooling loads. Furthermore the relative time lag could reduce heating requirements in some seasons by maintaining the structure in higher than ambient temperatures and thus passively warm the indoor space if so required. In the same way passive cooling could occur, as a heavy construction will always delay its thermal response to outdoor conditions leading to higher temperatures often many hours after ambient peak ones.

In order to estimate this time lag in the response of a construction element we have included an annual, a summer and winter month and week graphic presentation of the tool's results in order to find out the way in which various constructions respond relative to their thickness and outdoor surface absorbtivity values.

6.1 Roof Absorbtivity variation

In northern Europe typical absorbtivity values for building constructions and especially dark coloured roof tiles are usually 0.9-0.8 [7] which is reasonable as the reduced amount of solar gains could support in maintaining temperatures in higher values and thus reducing the heating load.

In southern Europe depending on the local climatic conditions values are often reduced in order to protect the building from over heating especially in the summer period.

Going back to literature and entering a very low absorbtivity value of 0.2 roof temperatures seem to agree with experimental values bearing in mind testing is at 1000W which may be slightly lower than total solar radiation introduced in this tool in the summer period. However this is offset by the fact that roofs in current studies are usually considered to be adiabatic meaning no heat is transferred through the structure [8], which is not the case of the presented tool.

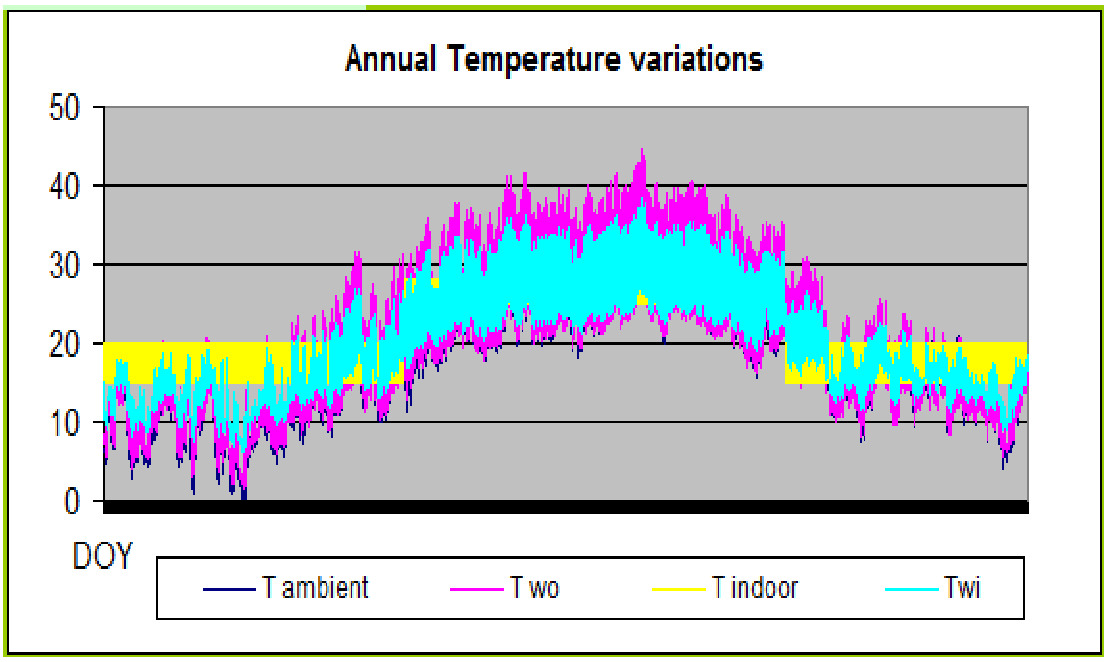


Figure 6.1-1

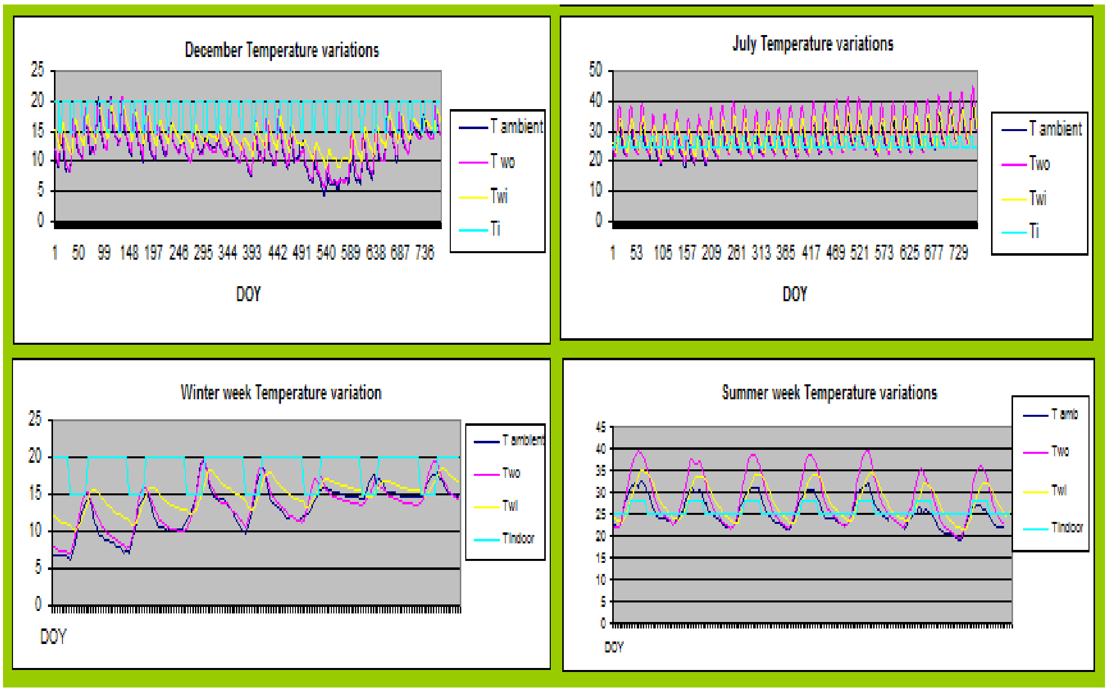


Figure 6.1-2

In order to assess the effect of absorbtivity on a building construction's inner and outer surface we have introduced a high, medium and low absorbtivity value to the tool and have come up with results illustrated in the following graphs:

High absorbtivity α = 0.8

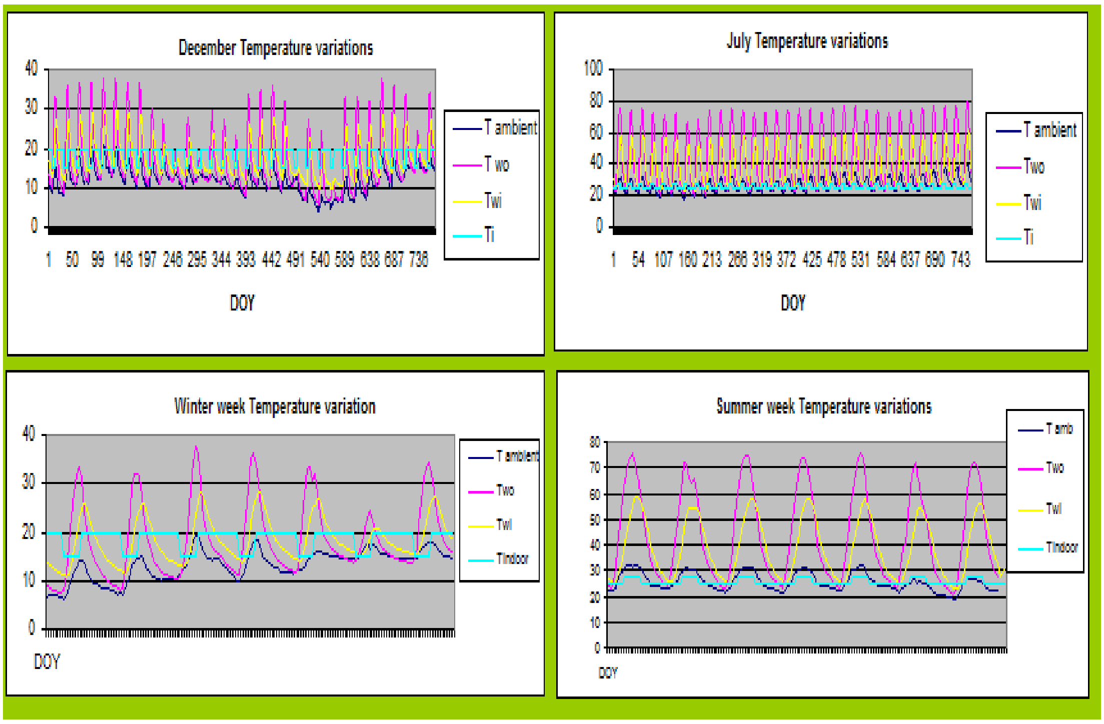


Figure 6.1-3

Moderate absorbtivity α = 0.5

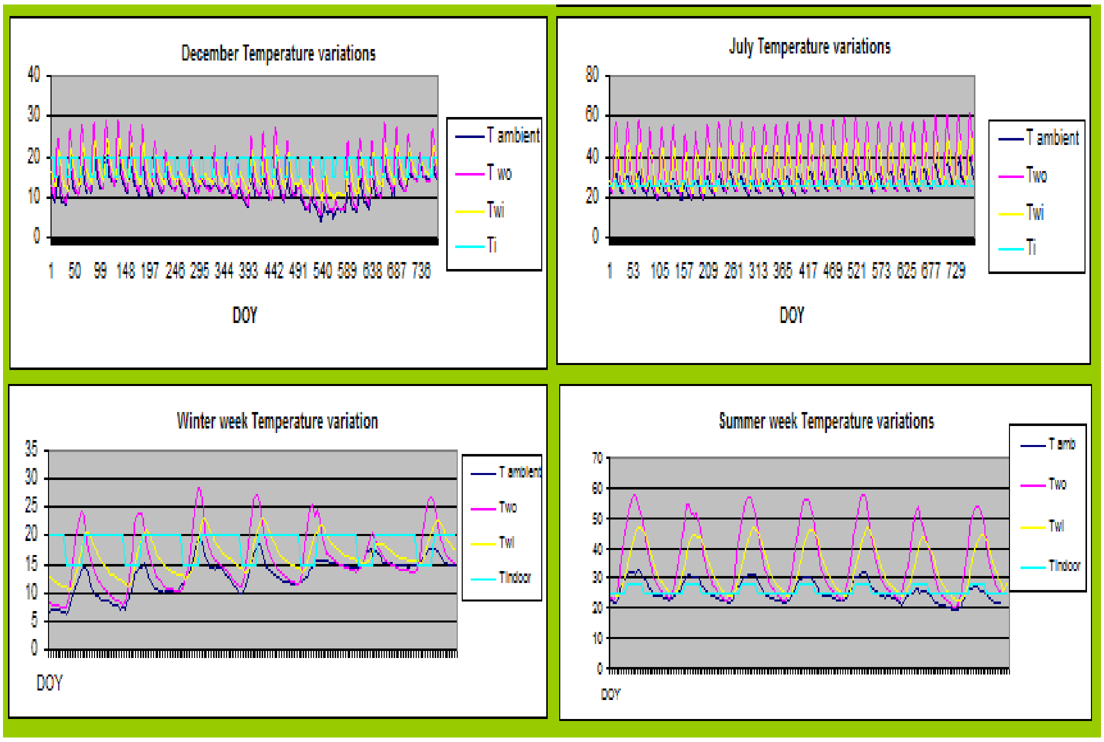


Figure 6.1-4

Low absorbtivity α = 0.2

(As shown above in the first set of graphs)

6.2 Construction thickness effect

In order to present the effect of thickness of a construction element 3 different thicknesses have been chosen and are the following:

Thickness of 0.1m

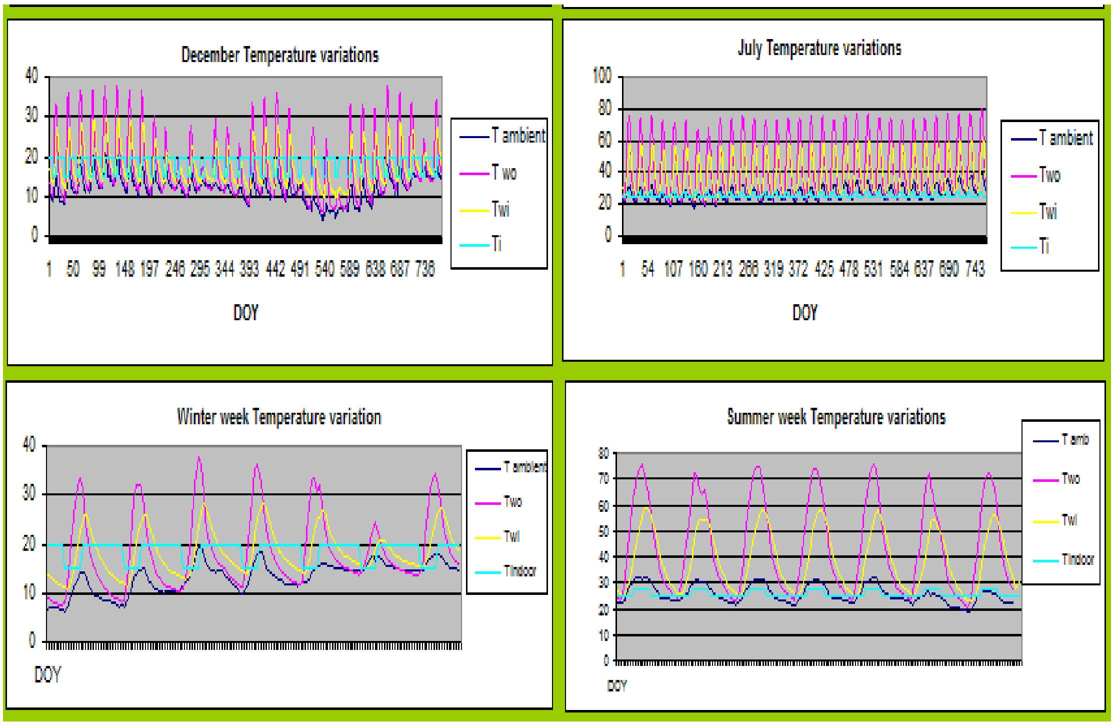


Figure 6.2-1

Thickness of 0.2m

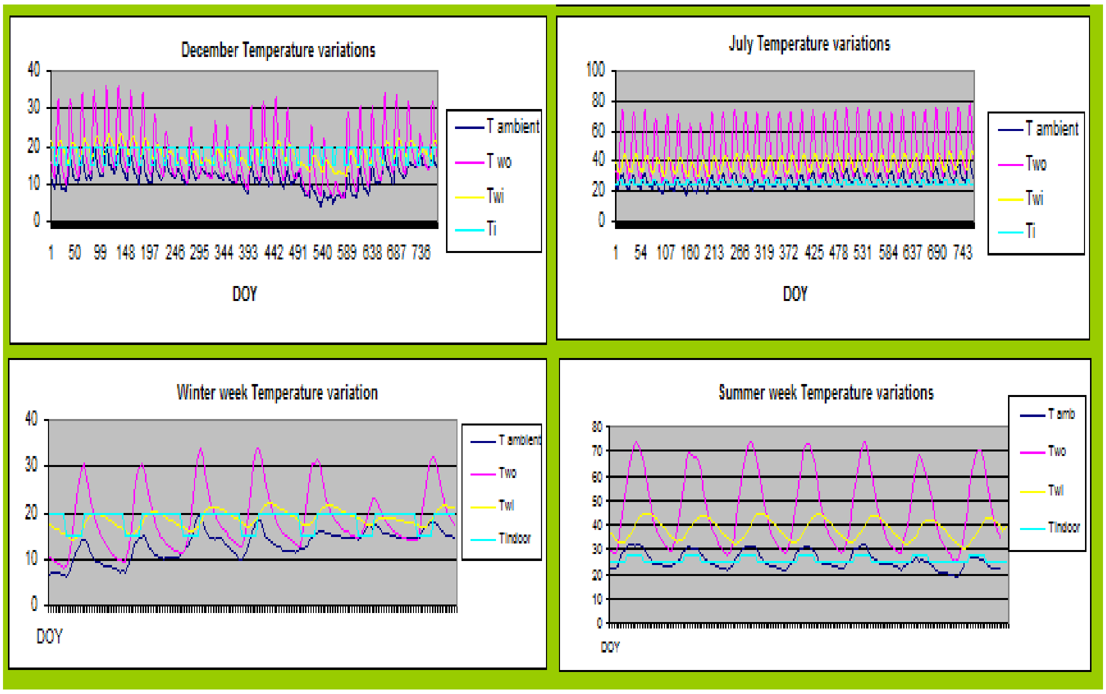


Figure 6.2-2

Thickness of 0.3m

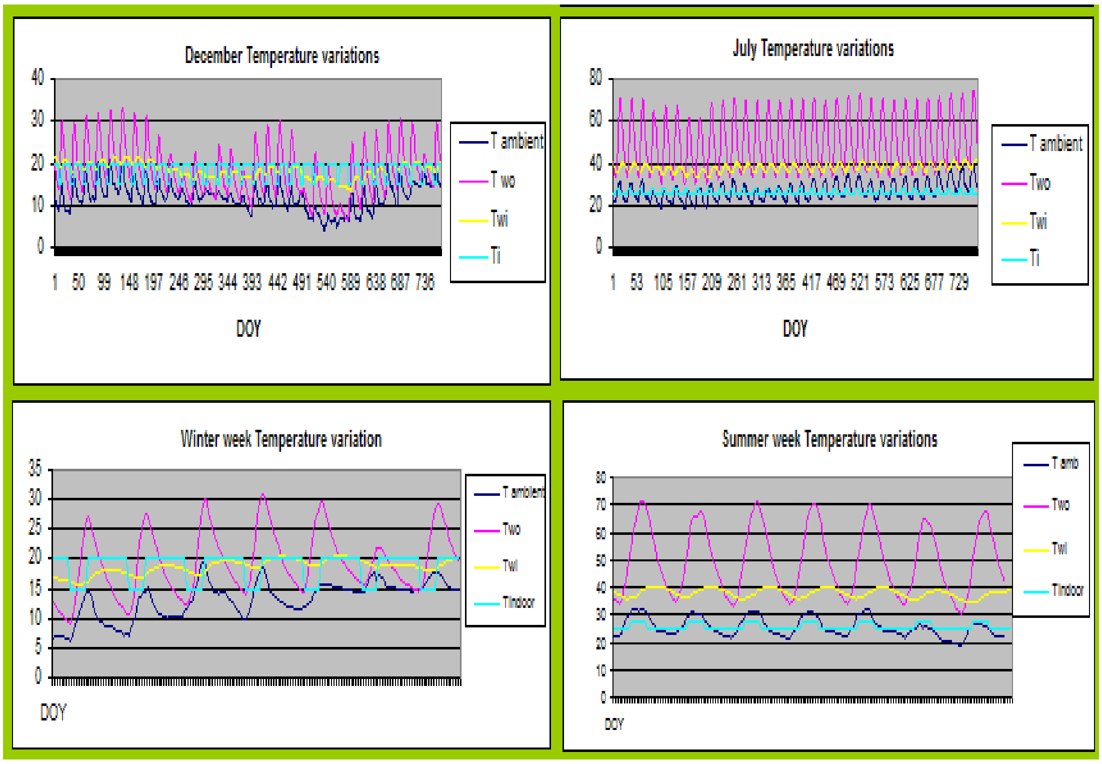


Figure 6.2-3

7 Discussion and concluding remarks

7.1 General

Although the annual output results do not appear to be very enlightening, it is quite evident from the summer and winter monthly graphs that this tool has not managed to successfully detect seasonal thermal storage.

Even when the wall thickness of the total wall – roof – floor area is considered to be 0.3 m which would mean a significant amount of thermal mass on the structure, the temperatures of the 2 nodes introduced in the construction do not seem to be storing any heat for longer time periods.

7.1.1 Absorbtivity effect

When the construction elements have a low absorbtivity value, both inner and outer node temperatures seem to follow the ambient temperature quite closely with the outer node always with a small time lead relative to the chosen moderate construction thickness of 0.1 m. Naturally, the outer node temperature variation is greater in summer but does not exceed the ambient temperature more than 10 deg C at noon as it has absorbed, apart from the ambient temperature (heat transfer through convection), a significant amount of solar radiation.

The energy absorbed moves gradually towards the inner surface which comes at its peak in the early afternoon. The indoor node reduced fluctuation is due to the constant conditioned indoor space temperature Ti in contrast to the outdoor which, apart from convection with the ambient air, emits heat also to the sky through radiation.

As absorbtivity values rise, so do peak inner and outer note temperatures. Specifically in summer, even with a moderate absorbtivity value, inner and outer surfaces rise over 20 and 25 deg C respectively over the ambient temperature. Conventional absorbtivity values of 0.8 lead construction temperatures to rise as high as 40 and 30 deg C over ambient temperature at peak hours respectively.

7.1.2 Thickness effect

When assessing the thickness parameter, a common value of α=0.8 is introduced regarding the absorbtivity of the construction's outer surface since this is the most common value even in southern Europe especially due to aging of even brighter colours applied to the roof.

Due to the current simplified equation (estimating the time lag), which would present realistic results for a wall thickness between 0.1-0.3 m and the fact that the precision of the tool for hourly time step data is not ideal for a wall thickness less than 0.3 m, results might deviate (based on the Fourier and Biot equations relating thickness and time step to the accuracy of results). Nevertheless the effect of increasing the thickness under particular climatic conditions shall remain evident in a daily even weekly basis after the better observation of the data output.

Taking a closer look to the graphs of chapter 6.2 we may notice that for the winter monthly period, especially between time steps 520-620 hr, the temperature of the indoor node of the construction tends, as we increase the thickness gradually from 0.1 to 0.3, to maintain relatively constant temperatures irrelative to the significant fall of ambient temperatures occurring outdoors. This proves that thermal storage may occur when wall thickness is increased from 0.1 to 0.3 m at least in a monthly basis.

As far as the weekly effect of the increase of thermal mass, the following table shows an important decrease in the maximum and minimum temperature values (of a summer week where over heating in Athens is a serious issue) as constructions become thicker and the higher temperatures are moved from roughly 1 h in the case of 0.1 m to 4 h and 6 h in the case of 0.2 m and 0.3 m respectively.

This is very important since lower peak temperatures are experienced instead of noon at 16:00 or 20:00. This can be handled, less energy will be consumed off the peak energy demand. National grid can be relaxed and blackouts avoided as well as government investments concerning grid power output increase, even greater funds increasing further its power output.

Construction Temperature Response (α=0.8)			
thickness (m)	*time delay (hr)*	T_{wo} (min-max) (deg C)	T_{wi} (min-max) (deg C)
0.1	1	25-75	28-58
0.2	4	28-71	32-43
0.3	8	34-70	36-40

Table 7.1.2-1

7.2 Limitations

Due to time limitations the current state of this tool is not capable of evaluating the thickness effect on differently oriented or inclined surfaces. Varying construction thickness, depending on surface orientation, i.e. Northern wall surfaces absorb small amounts of solar radiation which would make it unwise to increase thermal mass in order to reduce a building's cooling load in summer.

7.3 Other relevant work

Akbari - Levinson have developed a tool as part of the cool colours project [14] which estimates roof surface temperatures in constant outdoor conditions based on the ASTM standard E 1980.

Akbari - Levinson have done extensive research partially in collaboration with the University of Athens on various materials applied on buildings and the surrounding surfaces of the urban environment focused on their reflectivity/emissivity values and the resulting surface temperatures. A number of white and coloured coatings have been developed and tested (reflective coatings) and have been estimated to have impressively low temperatures when compared to conventional (8).

Their tool's interface is illustrated in the following image:

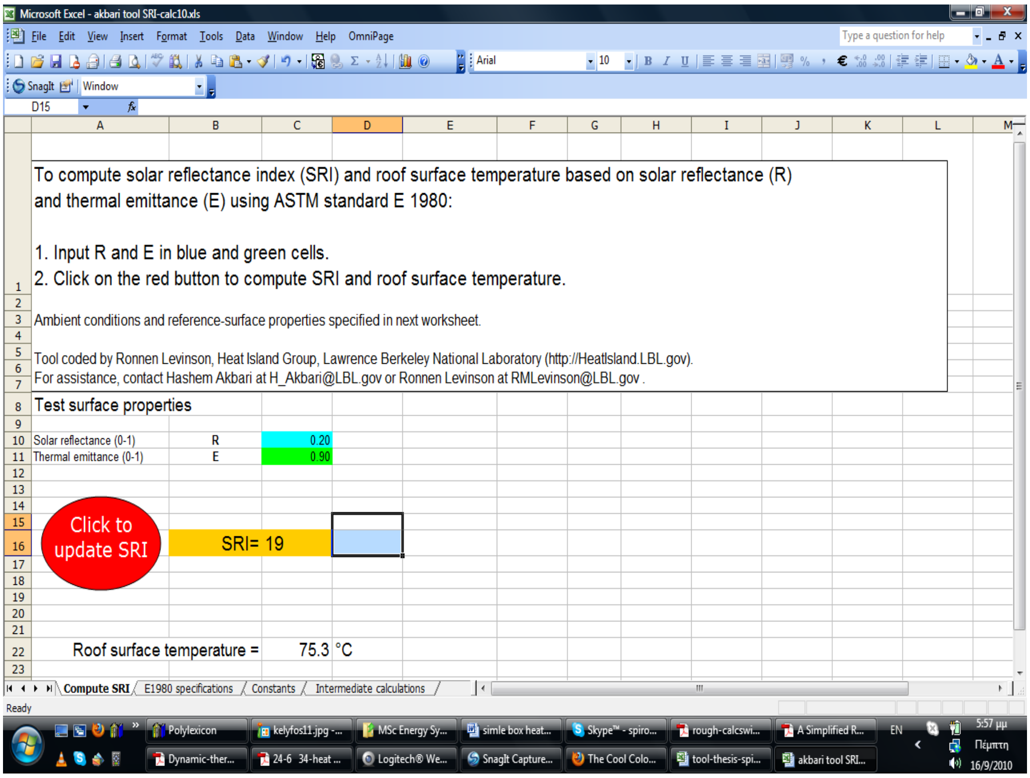


Figure 7.3-1: Akbari – Levinson tool interface 2005 [14]

One important simplification considered in this attempt to estimate the surface temperature of a building roof is its assumption to be adiabatic due to adequate insulation.

A results comparison has been followed through regarding a summer day hour between their tool and the one developed for this project.

Specifically regarding the day of year 180 at noon, the Athenian solar radiation value (1090W) for that specific time step was introduced with the according ambient temperature of 32°C. The following graph has been produced illustrating the variation of outdoor surface temperatures for various reflectivity values.

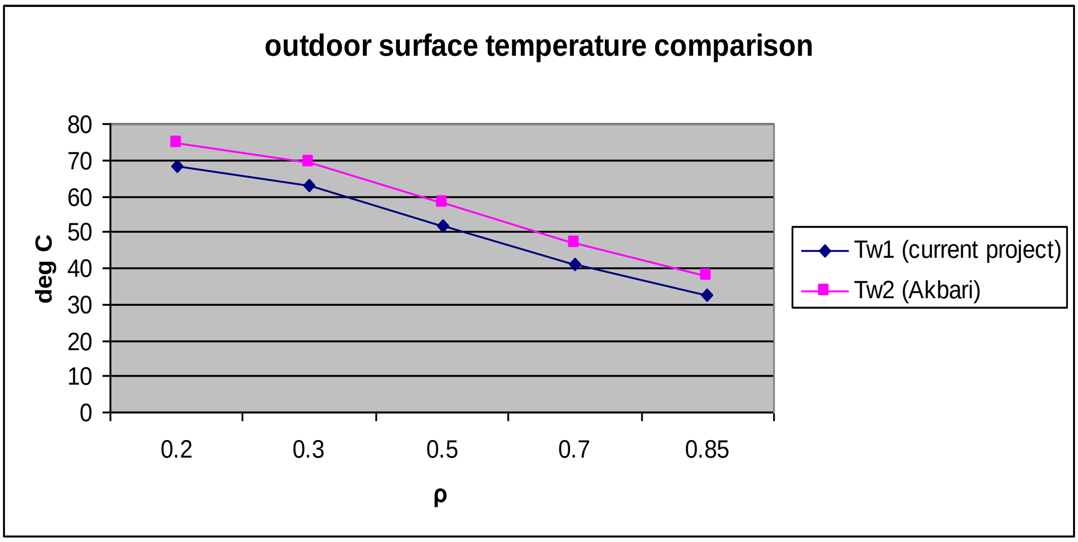


Figure 7.3-2

As expected, Akbari – Levinson, having considered no heat transfer through the wall, have come up with some constantly higher values (roughly 6 deg C or 8-15% higher). These values obviously would have been significantly higher if outdoor surface inclination and orientation, as well as specific convection heat transfer coefficients, were to be included. That is because Akbari's estimations are referred to horizontal surfaces, which is not the case of the tool currently presented in this thesis.

7.4 Future work

Material variation

- Try aerated concrete from my greek dissertation. (Try to introduce insulation on indoor and outdoor surface through adding a L/K with insulation conductivity)
- Comparison of excel tool output to reported values from simulations or experimental data..
- Increase precision by specifying orientation / inclination of building constructions regarding incident solar gains and convection heat transfer coefficients. Relate convection coefficients to wind speed.

- Develop an Espr similar box model to compare wall and indoor temperature values after introducing espr equations applied.

- Consider various openings' diameters scenarios and shading factors' effect on indoor solar gains. Various glazing scenarios could be considered with different G, U – Values.

- Ground temperature yearly variation could be included in heat transfer calculations to conclude on the importance of ground insulation in southern and northern European climatic regions.

- Introduction of northern Europe climatic data (i.e. Glasgow) and conclude on the effect of ambient air and lower ground temperatures in construction temperature fluctuations around the year.

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