DIPLOMARBEIT

# Thermal and Visual Performance of Vernacular Revival Buildings in Plovdiv, Bulgaria

unter der Leitung von

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# KURZFASSUNG

Die Erschöpfung der Naturressourcen in Kombination mit der Klimakrise und der globalen Erderwärmung sind unter den zentralen Faktoren, die die nachhaltige Entwicklung und Energieeffizienz in fast allen Bereichen des Lebens notwendig gemacht haben. Da das Bauwesen zu den größten Umweltverschmutzer heutzutage zählt, ist die Untersuchung und Erforschung von alternativen Baupraktiken als diese, die aktuell eingesetzt werden, von wesentlicher Bedeutung. Die historischen Gebäude in Plovdiv, Bulgarien repräsentieren einheimischen Gebäuden in traditionellem Baustil aus der Zeit der Wiederbelebung Bulgariens. Sie haben den Test der Zeit überstanden. Zudem haben viele davon die Integrität und die Vollständigkeit wie vor Jahrzehnten bewahrt. In den letzten Jahren hat das zur Steigerung des Interesses seitens der architektonischen Gemeinde geführt. Sie werden als eine der Quellen nachhaltiger Architektur angesehen – entworfen und konstruiert mit lokalen und natürlichen Materialien und im Hinblick auf den Umweltkontext. Der Schwerpunkt dieser Forschung liegt auf dem Wärmeverhalten und der optischen Performance von fünf bulgarischen Volksbauten in traditionellem Baustil aus der Zeit der Wiederbelebung von Plovdiv, sowie auf dem thermischen und visuellen Komfort, den sie ihren Bewohnern hypothetisch bieten. Um eine mögliche Verbesserung der Gebäudeleistung zu untersuchen, werden fünf Fälle pro Gebäude simuliert - zusätzlich zum Basisfall werden auch vier weitere mit unterschiedlichen Optimierungsoptionen untersucht. Der EEW-Fall umfasst den Ersatz der ursprünglichen Einscheibenfenster durch energieeffiziente und die SW-, H- und EPS-Fälle umfassen die Isolierung der thermischen Hülle der Gebäuden mit Schafwolle, sowie Hanfwolle- bzw. EPS-Isolierung. Alle Fälle werden mit einer parametrischen Simulationssoftware simuliert, um die Wärmeleistung der Häuser zu untersuchen. Die beschriebenen Leistungsindikatoren sind Temperatur und relative Luftfeuchtigkeit, jährlicher Heizwärmebedarf, interne und solare Gewinne, Übertragungs- und Luftwechselverluste sowie die Möglichkeit einer Überhitzung im Sommer. Die Basis- und EEW-Fälle werden verwendet, um das Tageslicht anhand der Beleuchtungsstärke und des Tageslichtfaktors als Schlüsselindikatoren zu bewerten. Die Ergebnisse zeigen, dass die fünf Gebäude in ihrem derzeitigen Zustand eine zufriedenstellende Performance leisten und die aktuellen bulgarischen Energieeffizienzanforderungen erfüllen. Der Austausch von den Fenstern bietet einige Verbesserungen, aber die bedeutendste Änderung kann bei der Isolierung der thermischen Hülle gesehen werden. Von den drei Isolierungstechniken bringt

die Schafwollen die größte Veränderung mit sich und ist gleichzeitig eine sehr nachhaltige Option. Auf die andere Seite ändert die Optimierung der Tageslichtdurchlässigkeit nicht signifikant. Die Ergebnisse der Simulationen in dieser Masterarbeit legen jedoch nahe, dass eine Verbesserung der thermischen Hülle die Gebäude in Bezug auf Leistung und thermischen Komfort in Konkurrenz zu den neuesten Technologien bringen würde.

# ABSTRACT

The depletion of natural resources in addition to global warming have created the necessity for sustainable development and energy efficiency in almost every aspect of our lives and since construction is one of the main pollutants nowadays, it is important to explore other building practices than the ones we are currently dealing with. The historic buildings of Plovdiv represent the Bulgarian vernacular buildings from the Revival period. They have withstood the test of time, many of which with the same integrity they had decades ago. This has made them very interesting to the architectural community in recent years as they are thought to be one of the founts of sustainable architecture – design with local natural materials and with regard to the environmental context. The main focus of this research is the thermal and visual performance of five Revival period vernacular buildings from the Plovdiv area as well as the thermal and visual comfort they would hypothetically provide to its occupants. In order to explore possible enhancement of the buildings' performance four cases with different optimization options were simulated in addition to the base case – the EEW case includes replacement of the original single pane windows with energy efficient ones, the SW, H and EPS cases include insulating the thermal envelope with sheep wool insulation as well as hemp wool and EPS insulation respectively. Each building's five cases were simulated using parametric simulation software in order to explore the thermal performance of the houses. The discussed key performance indicators are temperature and relative humidity, annual heating load, internal and solar gains, transmission and air change losses as well as the possibility of summer overheating. The base and EEW cases were also used to assess daylight using illuminance levels and daylight factor as key indicators. Results show that even in their current state the five buildings perform satisfactorily and do meet the current Bulgarian energy efficiency requirements. The replacement of windows provides some improvement but the most significant change can be seen with insulating the thermal envelope. Out of the three sheep wool brings the biggest change while being a very sustainable option. On the other hand, none of the optimizations change the daylighting situation significantly. However, the study suggests that improving the thermal envelope would put the buildings in competition with the newest technologies in terms of performance and thermal comfort.

**Keywords:** Vernacular; Revival Architecture; Plovdiv; Thermal Performance; Daylight; Energy Efficiency; Sustainability; Dynamic simulation; Building Comfort

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*Dedicated to my son Philip*

# CONTENTS

# 1 INTRODUCTION

## 1.1 Overview

“*In the world of modern designs, vernacular designs have their charm. One of the significant characteristics of a vernacular design or architecture is that it mixes nicely with the environment and geographical location, suites well to the climatic conditions*” (Janetius, 2020). In times when cities are crowded with buildings and the building industry is one of the biggest pollutants in the world the exploration of sustainable practices is of high necessity. Vernacular architecture is considered to be one of the primary examples of what we now call sustainable development – local natural materials, craftsmanship and acknowledgment of the environmental context is what architects link to the Revival vernacular buildings. With the development of technology building techniques have gone through major change (industrialization of materials production, construction, etc.) which inevitably led to more prefabrication and less local craftsmanship. "*All over the world, regardless of climatic context, buildings became more similar*" (Fernandes et al., 2019). The traditional construction techniques from that period are still present, mostly in the rural areas since the economic growth of the cities has resulted in lack of space and thus the necessity for high rise buildings. But in the historic areas such as the Old Town of Plovdiv most of those buildings remain intact providing a glimpse of a sustainable city. Those remaining buildings have withstood time, change of climatic conditions and overall exploitation and exploring those building practices and implementing them in current technologies could make them even better providing a more sustainable alternative for construction.

## 1.2 Motivation

Plovdiv is the second largest city in Bulgaria and is located on the Maritsa River in the Thrace region. It is often referred to as “the city of the seven hills” because of where it was established – under seven syenite hills one of which was destroyed (Markovo tepe). Settlement around the area has started more than 8000 years ago and has not stopped since which makes it one of the oldest cities in Europe in terms of population continuity. Since then, Plovdiv has gone through many transformations, changed many names but has not stopped growing and evolving.

After the Ottoman Empire conquered the Balkan Peninsula in the 14th century the city's appearance has totally changed and thus after the wars opportunities for new construction have risen.

At that time during the 19th century the Revival period started and new buildings were built many of which still stand today and are considered architectural and cultural heritage. Rich merchants invested in the construction of these enormous highly decorated houses and although they look more like royal residences, they still bear the qualities of the traditional Bulgarian houses. The geography of the town (located on the Maritsa river and between Sredna Gora and Rhodope mountains) resulted in mainly wooden construction with the addition of thick stone walls and clay – entirely local natural materials which nowadays is what is believed to be entirely sustainable practice – is one of the reasons that lately those buildings have become of high interest among the architects. Contrary to the newly found interest in the vernacular Revival building practices not long ago those landmarks were considered as nothing more than a possible new construction lot with great location and as such many were destroyed. Even though the building society finds much value in those historical buildings, their exploration has not spread much beyond their architectural qualities. The advantages of such constructions are believed to be many – from decrease of costs and $CO_2$ emissions, to sustainability and reduced heating and cooling needs. Therefore, the goal of this study is to evaluate the thermal and visual performances of five examples of the traditional Plovdiv Revival vernacular building resulting in actual numerical values that could stand as a base for further research and future development and implementation of those construction practices into new buildings.

## 1.3 Background

### 1.3.1 Scientific background

Major economic growth and scientific progress, albeit rather important, have led to dangerous patterns of energy consumption resulting in depletion of natural resources and addition to global warming. In times when the impact on nature that human progress had is obvious, it is essential that society learns how to mitigate those devastating effects. The building sector has contributed to a large portion of the energy consumption increase in the last decades. Therefore, sustainable building design has been a main focus amongst scientists. Since vernacular architecture is not dependent on high energy-consuming systems for heating, cooling, lighting and ventilation, such buildings are being researched thoroughly. Shaped by local craftsmanship, climate and historical background vernacular buildings are not only beautiful but also interesting as possible examples for entirely sustainable building design.

The most thorough research that exists on the subject especially for the Bulgarian architectural heritage buildings has been done by Rosen Savov. According to him many different principles and construction practices are used for softening and correcting the effect of the harsh weather conditions but also for collecting and later on using the solar radiation (Savov and Nazarski, 2006). Savov has studied the urban planning, architecture and construction of the Bulgarian Revival vernacular buildings supporting the idea about their sustainability and possible energy efficiency.

A research conducted in Romania about the thermal performance of traditional buildings suggests that considering their age those buildings perform on a satisfactory level. “*The shortcomings can be corrected by implementing simple solutions. Providing the building envelope with an additional thermal insulation layer, ensuring air tightness and waterproofing can make the traditional houses meet current thermal performance standards*” (Ciocan, 2018).

Another study conducted from scientists from the Islamic Azad University suggests that vernacular buildings are "*generally healthy buildings where human-nature relationship is solved in a simple and functional way*" (Mohammadi and Gharehaghaji, 2017). According to this research the design practices used in vernacular buildings around the world use the environment to create the necessary living comfort via natural ventilation, thoughtful use of space and indigenous materials.

The thermal performance analysis of vernacular houses in the Israeli coastal plain showed that the examined central hall buildings do not provide the necessary comfort required by the current standards although "*conditions could be easily enhanced today with relatively minimal efforts*" (Aleksandrowicz, 2012).

A research about thermal behavior of vernacular stone buildings in Greece led to the conclusion that in their current state, although the buildings offered "*the best possible living conditions*" (Tsiouni, 2014) during the summer, they do not perform quite as well during the winter season when additional heating is necessary to obtain the desired comfort.

Prior studies suggest that vernacular architecture is a subject of interest of many researchers around the world, Bulgaria included. Finding value in the existing building stock and possibly improving the living conditions of many could help not only protect the architectural heritage of Bulgaria and its local traditions, but also to greatly reduce the total primary energy use and $CO_2$ emissions of the country from the building sector.

### 1.3.2 Historical background

The Bulgarian Revival is a period of economic, cultural and political rise which inevitably led to diverse architectural boom. It comprises of the last century of the Ottoman rule over Bulgaria (end of 18th and 19th centuries) which ended in 1878 with the Russo-Turkish liberation war (Daskalov, 2004). During this period the old and strategically positioned Bulgarian cities were developing in a very fast pace. Architecture in Bulgaria experienced growth like never before. Although many of the architectural heritage buildings from that time bear the features typical for the epoch, this did not create a uniform style and each place have their unique individual image in relation to its environment. Residential buildings are a major part of the heritage Revival buildings. The vast variety of Bulgarian houses is formed by the local construction techniques and building materials, different in structure, color and technical properties. Thus, they could be subjectively separated according to their location to “zapadna”, “tetevenska”, “trevnenska”, ”koprivshtenska”, “zheravnenska”, “rhodopska”, “banska”, “strandjanska”, “chernomorska” and “plovdivska” house (Publishing collective, 1965) /literally meaning “western”, “from Teteven”, “from Tryavna”, “from Koprivshtica”, “from Zheravna”, “from Rhodope”, “from Bansko”, “from Strandja”, “from Black sea”, and “from Plovdiv”/. As the biggest trading center in Bulgaria during the first half of 19th century, Plovdiv is one of the places where the development of the Bulgarian Revival house was at its peak.

Plovdiv is a city with millennial history, claimed to be contemporary of Troy and Mycenae and more ancient than Rome, Athens and Constantinople. It’s most known with one of its old names Philipopolis (Greek: Φιλιππούπολη; Turkish: Filibe „Philip's Town“). The name comes from the era of Philip II of Macedonia during which time the city has gone through major development. Plovdiv is most famous with its cultural heritage (European capital of culture 2019) dating back to the Thracian population which is the oldest one on the Balkan peninsula, according to archaeological written sources. Although the city has remains from nearly every ancient period, its most well-preserved part is the „Old city“ situated on three of the hills and home to many buildings from the Bulgarian Revival period. *„Its stylistic characteristic is a unique variety of the Balkan vernacular architecture from the end of the Ottoman domination – XVIII-XIX centuries“* (UNESCO World Heritage Centre, 2004). The hills are not very high (the highest one Djendem tepe is 283m above sea level) which allowed the area to be filled with residential buildings making an interesting amphitheatrical landscape. Those houses represent not only the city but also the people living there, their customs, habits, culture and style. Contrary to most places around Bulgaria the people from Plovdiv have given up farming in favor of the city life - from craftsmanship and trading to cultural gatherings, private and public events and formal celebrations, all influenced by the life in Tsarigrad (Constantinopole, present Istanbul, Turkey), Vienna and other European towns. This style of life had a major impact on the residential building design and planning.

Previous research has led to the separation of two distinct types of the typical Plovdiv house – the asymmetrical house and the symmetrical house. The asymmetrical houses were developed earlier, up until the second half of the 18th century and typically included 2 or 3 rooms situated on 2 storeys and an open veranda („chardak“) which in the later examples is closed with windows. There are a few variations of this type of vernacular house – one-storey house, two-storey house with an outside staircase in the „chardak“ or with an inside staircase, as well as houses with entirely open or entirely closed „chardak“ (Figure 1). All of the oldest buildings from this period belong to the asymmetrical house type and are a typical example of the open Balkan house.

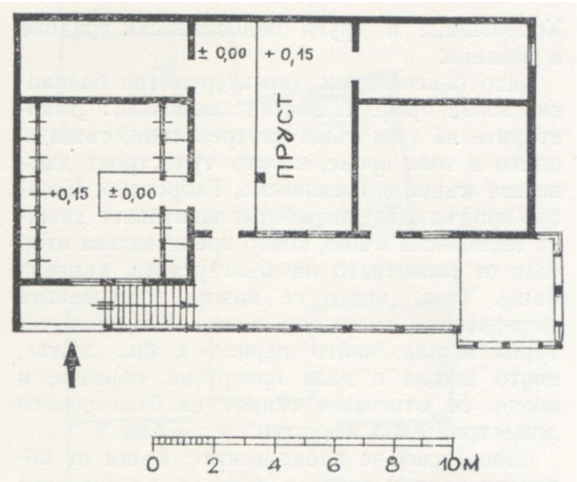


*Figure 1 Asymmetrical house (Peev, 1960)*

The symmetrical houses appear during the end of the 18th century and the beginning of the 19th century. Their strongest feature is the symmetry in the planning and the facades. As typical vernacular houses they were influenced by the environment and their owners‘ needs and thus can be separated in three groups: symmetrical houses built on the street border (Figure 2), symmetrical houses built within a patio (Figure 3) and symmetrical houses with mixed facade and planning (not completely symmetrical plans and facades due to terrain or other difficulties). Some of them have a round salon called “hayet” and some have a rectangular one around which the house plan is developed. "*Usually four rooms flanked the hall on both sides; one of which was used for guests, one was a ladies’ reception, other – a study of the owner, etc. Those rooms had windows looking into the hall*" (Raycheva, 2012). This type of “modern” architecture influenced the residential construction in the towns surrounding Plovdiv making symmetry in general a well desired feature.

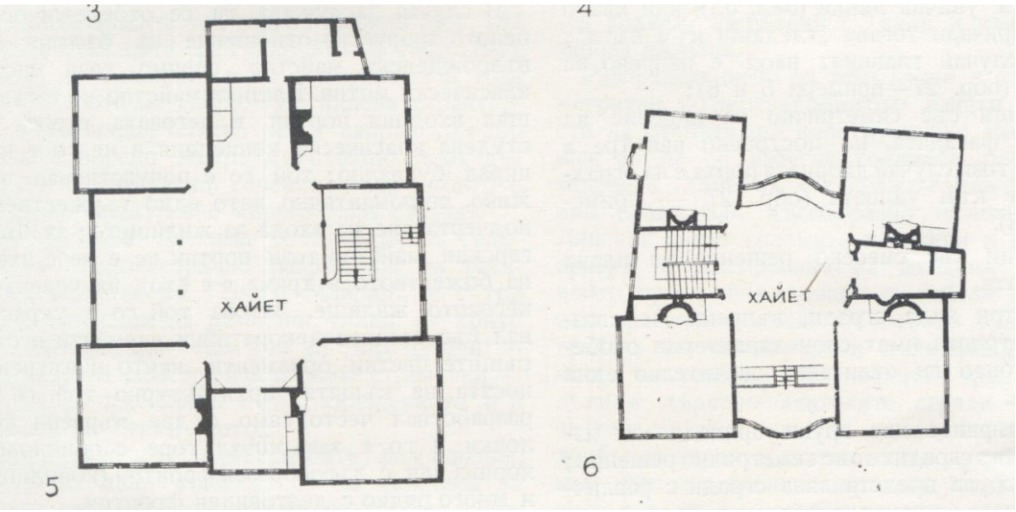


*Figure 2 Symmetrical houses built on the street border (Peev, 1960)*

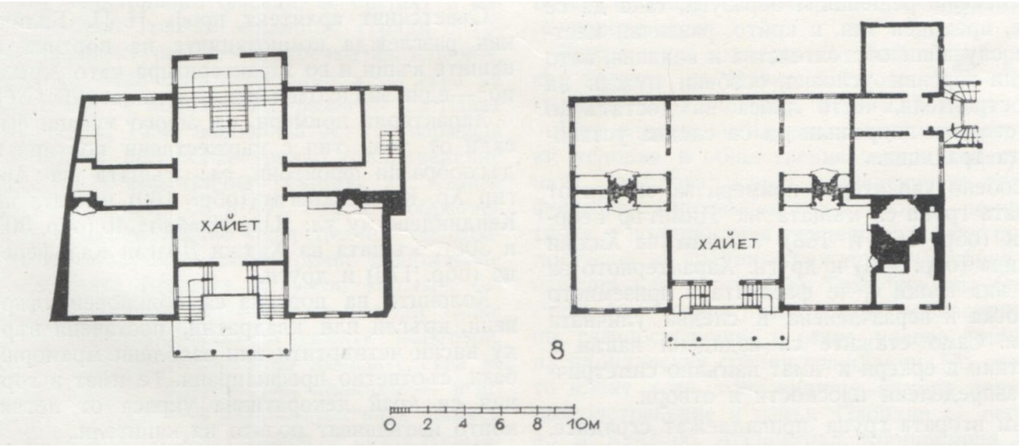


*Figure 3 Symmetrical houses with a patio (Peev, 1960)*

The Bulgarian architects and builders at that time were strongly influenced by the Italian Renaissance and Baroque in Western Europe and Tsarigrad (present Istanbul, Turkey) and implemented such features in their new constructions. This is visible in the design of the buildings including defined symmetry axes, the position of the staircase, the concave and convex façade elements, oval plan features and so on. Thus, the Bulgarian Revival house "*serves as a testimony to the close contacts that the Slavic Christian communities of the eighteenth and nineteenth centuries had with Turkish and Muslim-dominated areas*" (Koller and Koller Lumley, 2014).

Major characteristic of the Revival house is its wooden frame construction of the upper floors and stone masonry in the ground and basement floors which were erected up to 1.50 m from the ground. The timber walls were constructed with various wooden frames of vertical and horizontal posts with 0.7 – 0.8 m of space between them, filled with mud bricks or stone rubble, plastered and decorated on both sides. The timber roof construction had overhanging eaves which is a typical feature for the Bulgarian vernacular houses, so typical that it is to this day used as a synonym of “home”. It is not only a construction element which joins the walls with the roof but it is also used for shading and walls protection. Usually, the roof was covered with ceramic tiles. The construction properties of the timber roof allowed the interior to develop with long structural bays making long salons (“hayet”) with various planning shapes (Figure 4).

The symmetrical house developed well during the late Revival period to get to the palace-like town houses that we know today from Plovdiv. Local merchants living in-between Vienna and Plovdiv have become quite wealthy allowing them to invest in such grandiose houses. Their interior was highly decorated with wooden carved ceilings, doors, windows, fireplaces and furniture as well as wall painting with different colors. The façades were also painted with bright colors and decorated with paintings directly on the plaster finish. The wooden window frames had wooden pediments hanging above them (Figure 5) and the windows themselves were covered with wooden shutters on the outside (Figure 6). The decorative niches “alafrangas” were often used as a space for the built Turkish heater “Jamal” which was sitting on a marble plate.

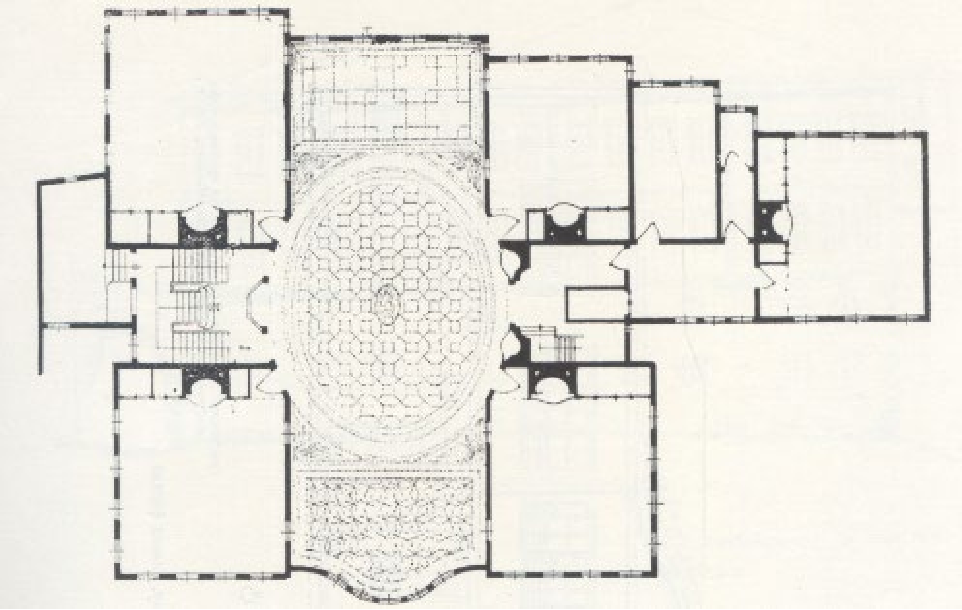


*Figure 4 Kuyumdzieva house  (Peev, 1960)*

*Figure 5 Kuyumdzieva house (Personal archive)*

*Figure 6 Kuyumdzieva house (Personal archive)*

### 1.3.3 Climate

The climate is specific due to the city's location (on the Maritsa River and between hills) creating mild winters and hot and humid summers (transitional subtropical continental). The average maximum and minimum temperatures are 30.3°C measured in July as well as 6.5°C measured in January. "*The average annual relative humidity is 73%, the highest in December – 86% and lowest in August – 62%*" (Plovdiv municipality, 2020).

Bulgaria is nominally separated into nine climatic zones (Figure 7). The zones are as follows: 1. Northern Black Sea; 2. Dobrudzha; 3. Northern Bulgaria – Danube river; 4. Northern Bulgaria – central part; 5. Southern Black Sea; 6. Southern Bulgaria – central part; 7. Sofia and Underbalkan valley; 8. Southern Bulgaria; 9. Southwestern Bulgaria (Ministry of regional development and public works, 2015).

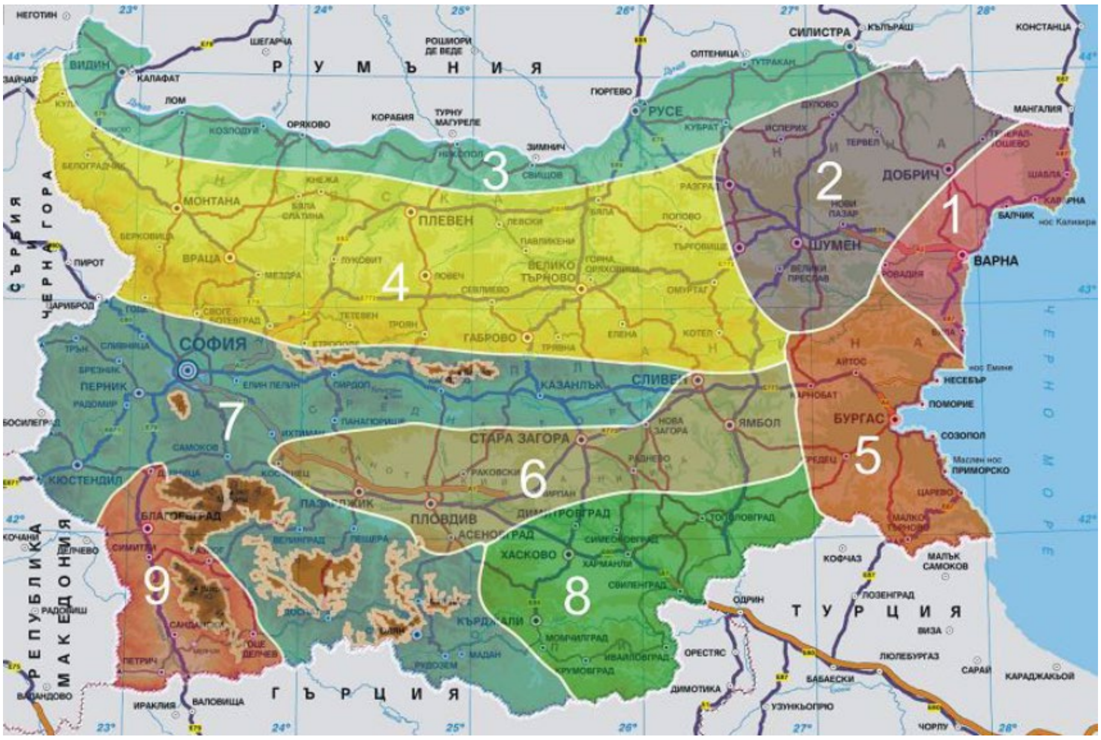


*Figure 7 Climatic zoning (Ministry of regional development and public works, 2015)*

Important values for the climate specifics in each zone are shown in Regulation №7, Annex 2 (Ministry of regional development and public works, 2015). Plovdiv is located in the 6th zone – Southern Bulgaria – central part. The values for the 6th zone are shown in Table 1. Additional climate data necessary for the simulations which was visualized with the climate software Meteonorm (Meteotest AG, 2021) is shown in Appendix D.

*Table 1 Basal climate values by climatic zone 6 (Ministry of regional development and public works, 2015)*

| Heating season | Start: 24 October<br>End: 6 april | | | | Calculative exterior temperature | | | | -15 °C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Degree days (DD) with average building temperature of 19 °C | | | | 2400 | | | |
| Month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
| Number of monthly calculation days | | | | | | | | | | | | |
| | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| Monthly average temperature, °C | | | | | | | | | | | | |
| | 0.2 | 1.8 | 6.9 | 12.4 | 17.4 | 21.3 | 23.7 | 23.0 | 18.7 | 12.8 | 7.4 | 1.9 |
| Monthly average relative humidity, % | | | | | | | | | | | | |
| | | | | | 69.3 | 66.3 | 60.7 | 60.0 | 65.7 | | | |
| Average sun radiation intensity on vertical surfaces, $W.m^{-2}$ | | | | | | | | | | | | |
| North | 27.7 | 38.5 | 53.3 | 68.1 | 78.7 | 86.1 | 83.8 | 76.7 | 61.8 | 44.0 | 29.7 | 23.5 |
| East | 58.5 | 71.8 | 84.5 | 97.9 | 111.1 | 130.2 | 126.6 | 130.7 | 111.1 | 78.2 | 56.4 | 47.0 |
| West | 58.5 | 71.8 | 84.5 | 97.9 | 111.1 | 130.2 | 126.6 | 130.7 | 111.1 | 78.2 | 56.4 | 47.0 |
| South | 109.5 | 118.4 | 111.4 | 97.3 | 91.8 | 103.9 | 103.5 | 129.6 | 142.0 | 121.0 | 100.5 | 88.5 |
| Horizontal surface | 69.5 | 96.9 | 132.8 | 171.0 | 199.1 | 232.7 | 226.8 | 228.2 | 177.3 | 111.1 | 70.9 | 55.3 |

# 2 METHOD

## 2.1 Overview

Technological advancement has led to significant development of building techniques. As the depletion of natural resources and global warming became a problem of the present as well as the future, scientists continue to explore the environmental performance of buildings in an attempt to reduce the energy consumption of one of the highest consuming sectors responsible for approximately 36% of all $CO_2$ emissions and 40% of the energy consumption (European Parliament and the Council of the European Union, 2018). Attention on historical buildings has always existed as they are believed to have offered comfort to their inhabitants using elaborate building techniques as opposed to complicated energy consuming systems. "*Vernacular architectures in general, are relevant examples of bioclimatic design, embedding site-specific solutions for climate adaption*" (Finocchiaro, 2019). Thus, they could offer possible solutions for the architects and builders to implement in current designs in order to reduce the energy demand of the building sector.

The objective of this research is to evaluate the thermal and visual performance of Bulgarian vernacular buildings from the late Revival period under current weather conditions. Furthermore, possible refurbishment solutions would be explored and results with the improved thermal envelope will be compared to the non-improved cases.

## 2.2 Hypothesis

Previous research on the subject had led to the conclusion that vernacular buildings with their environmentally conscious design would perform well in comparison with modern energy-consuming buildings according to current standards. Good thermal and visual performance is not solely dependent on complicated technology and electrical systems which is visible in present research about environmentally-friendly design, passive houses, zero-energy houses, etc. Therefore, it is possible that the assessed housing examples are fit to satisfy the needs of a modern household and if not completely, then they could do that with minimal improvements.

## 2.3 Parametric simulation

For the purposes of this study five different, typical for the Bulgarian Revival period, vernacular houses were chosen all from the historical “Old city” of Plovdiv. The chosen examples were digitally drawn using on-site measurement and some existing architectural drawings. A 3D model was created for each house so that it could later on be added to simulation software and perform the necessary analyses. Important data was gathered in order to best simulate the conditions under which the example houses would perform. Such data is: geographical parameters (latitude, longitude, altitude, sun position), climate parameters (weather file with real data collected throughout the years), measurements of the example houses, rooms use (heated/unheated), construction materials and finishes. All of this data was added to the simulation software - Rhinoceros 3D (McNeel, 2018) with Grasshopper (McNeel, 2019) plug-in and additional Honeybee (Roudsari, 2020a) and Ladybug (Roudsari, 2020b) plug-ins which are environmental plug-ins used by Grasshopper. They use EnergyPlus$^{TM}$ (International collaboration team, 2020) as a sub-software to do the requested simulations which is one of the preferred programs for thermal simulations and energy analysis. The plug-ins also use OpenStudio® (International collaboration team, 2021), Daysim (Reinhart, 2013), Radiance (McNeil, 2016) and Therm (Lawrence Berkeley National Laboratory, 2017) as sub-software for building energy and daylighting analysis.

The simulation was carried out in five cases: the buildings in their current state, the buildings after changing the windows with more efficient ones, the buildings after adding sheep wool insulation to the thermal envelope, the buildings after adding hemp wool insulation to the thermal envelope and the last one - the buildings after adding EPS insulation to the thermal envelope. The following parameters were considered for the thermal simulation – temperature, relative humidity, annual heating load, transmission losses, losses due to air changes (ventilation, infiltration), solar gains, internal gains. Also, the possibility of overheating during the summer months was evaluated. Although for most parameters monthly changes were considered, the results for the energy demand will be shown annually. Discrepancies can exist to an extent due to the necessary simplification of the building model, inaccurate measurements on site, inaccurate drawings or insufficient material data as well as the lack of accurate occupant behavior simulation possibilities.

For the visual simulation also the Rhinoceros 3D software with Grasshopper plug-in and Radiance as a sub-plug-in were used and the reviewed parameters were illuminance levels and daylight factor. The visual simulation was performed in two cases – with the current single-pane windows and with energy efficient ones.

Finally, the results were thoroughly processed and evaluated in order to prove or disprove the hypothesis.

## 2.4 Physics groundwork for energy and daylight evaluation

Building physics is in the basis of all energy simulations performed by the selected software. All types of heat transfer throughout a building influence its performance and affect the indoor climate and thus play a vital role for ensuring thermal comfort. „*Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment*“ (ASHRAE, 2020) and is important for health and productivity. Although quite subjective, because it depends on personal factors of the building inhabitants, it also depends on some environmental factors such as temperature, air speed, humidity, etc. Using the numerical representations of those factors many other parameters can be calculated. The calculation of specific building performance indicators necessary for the purpose of this research has the following physical relations expressed in equations:

- Material have specific properties and important ones for the purposes of this research are: thermal conductivity λ ($W.m^{-1}.K^{-1}$); density ρ ($kg.m^{-3}$); specific heat capacity c ($J.kg^{-1}.K^{-1}$)
- Thermal resistance of a multi-layered building element ($m^2.K.W^{-1}$)

$$Rt = \sum_{i=1}^{n} \frac{di}{\lambda \mathrm{i}}$$

*(Equation 1 Thermal resistance)*

where d is the thickness of the layer and λ is the thermal conductivity of the material layer.

- Thermal transmittance – U-value ($W.m^{-2}.K^{-1}$)

$$U = \frac{1}{Rsi + Rt + Rse}$$

*(Equation 2 Thermal transmittance)*

where Rt is the thermal resistance of the element, Rsi is the interior surface resistance and Rse is the exterior surface resistance (regulated in DIN EN ISO 6946 (Deutsches Institut für Normung, 2008)).

- Heat balance kWh (simplified equation)

$$Q = Qt + Qv - \eta(Qi + Qs)$$

*(Equation 3 Heat balance)*

where Q is the thermal load, Qt is the heat losses via transmission, Qv is the heat losses via ventilation, Qi are internal gains and Qs are solar gains and η is the efficiency of gains (depending on the type of the construction – massive, light weight, etc.)

- Transmission losses – conduction through the building element Qt (W)

$$Qt = \sum (A.U).(Tin - Tout)$$

*(Equation 4 Transmission losses)*

where A is the area of the building element, U is the thermal transmittance, $T_{in}$ is the inside temperature and $T_{out}$ is the outside temperature

- Air change heat losses Qv - due to ventilation and infiltration (W)

$$Qv = c_p.\rho.n.Vn.(Tin - Tout)$$

*(Equation 5 Air change heat losses)*

where $c_p$ is the specific heat capacity of air ($J.kg^{-1}.K^{-1}$), ρ is the density of air ($kg.m^{-3}$), $V_n$ is the ventilated net zone volume in $m^3$, n is the air change rate (ACH), $T_{in}$ is the inside temperature and $T_{out}$ is the outside temperature

- Solar gains Qs through the transparent building elements:

$$Qs = A.E.g.z$$

*(Equation 6 Solar gains)*

where A is the area of the transparent element in $m^2$, E is the incident solar radiation ($W.m^{-2}$), z is the reduction shading factor and g is the fraction of transmitted solar radiation (g-value for windows)

- Internal gains – from people, lights and equipment Qi:

$$Qi = q_i.A$$

*(Equation 7 Internal gains)*

where A is the zone area in $m^2$ and $q_i$ ($W.m^{-2}$) is the heat emission rate (regulated in norms, depending on type of building-houses, hospitals, schools, etc.)

- Operative temperature To (°C):

$$To = \frac{h_r . t_{mr} + h_c . t_a}{h_r + h_c}$$

*(Equation 8 Operative temperature)*

where $h_c$ is the convective heat transfer coefficient, $h_r$ is the linear radiative heat transfer coefficient, $t_a$ is the air temperature and $t_{mr}$ is the mean radiant temperature

- Relative humidity RH (%):

$$RH = 100 . \frac{P_w}{P_{ws}(t)}$$

*(Equation 9 Relative humidity)*

where $P_w$ is the water vapor pressure and $P_{ws}$ is the saturation pressure at a certain temperature.

- Daylight factor DF (%) – a quantitative measure of daylight illuminance:

$$DF = \left(\frac{E_i}{E_e}\right) . 100\%$$

*(Equation 10 Daylight factor)*

Where $E_i$ is the illuminance inside and $E_e$ is the illuminance outside

- Illuminance E (lux) or is the total luminous flux incident on a surface per unit area:

$$E = \frac{\phi}{A}$$

*(Equation 11 Illuminance)*

where ϕ is the luminous flux (lm) and A is area in $m^2$

## 2.5 Evaluated examples - description

### 2.5.1 House Hindlyan - (Къща Хиндлиян)

The house was built in 1835 for the Armenian Stepan Hildlyan. It is one of the few completely preserved in its original state symmetrical Plovdiv houses. Due to the irregular plot there is only one symmetrical façade (the one overlooking the patio) and the plan is not entirely symmetrical as well. Inside the patio there are a few smaller buildings with agricultural purposes that are part of the ensemble but not connected to the house. Only the house covers about 610 $m^2$ of space. It has thick stone foundation, timber construction with adobe bricks and three layers of plaster forming the façade finish. On the ground floor a wide portico protrudes inwards supported by two wooden columns. The “hayet” has a square shape and a wooden carved ceiling and is surrounded by three big rooms. The kitchen is also on the ground floor but in an additional building next to the rooms for the staff. The house is one of the few existing from that time that have a bathroom inside (Figure 11) - located on the first floor it was built on the principle of the Turkish “hammam” or the Roman hypocaust and is connected to the kitchen. It has a massive stone construction, ceiling domes and is entirely decorated with marble. A wide staircase leads to the second floor which consists of a big rectangular “hayet” (Figure 12) with a wooden carved ceiling, as well as four big rooms around it. Another innovation for that time except the personal bath is the water reservoir on the roof that collected rainwater for the household, sending the water to the kitchen and bathroom using pipes (Peev, 1960). The interior is especially artistic (Figure 13) and highly decorated with the traditional wooden carving as well as murals and frescos portraying landscapes from all over the world. Thick window frames, paintings and other decorations as well as solid iron and wooden doors are all features of the exterior (Figure 8,Figure 9 and Figure 10).

*Figure 8 Exterior (Personal archive)*

*Figure 9 Exterior (Personal archive)*

*Figure 10 Exterior (Personal archive)*

*Figure 11 Bathroom (Personal archive)*

*Figure 12 Interior (Personal archive)*

*Figure 13 Interior (Personal archive)*

### 2.5.2 House of Dr. Stoyan Chomakov – (Къща на д-р Стоян Чомаков)

*Figure 14 House of Dr. Stoyan Chomakov (Personal archive)*

The house was built in 1860 for Dr. Stoyan Chomakov and is a typical example of late symmetrical Revival houses. The ground floor includes a closed entrance area with a marble flooring, rectangular salon with a wooden carved elliptical ceiling, four rooms flanking the “hayet” and a grandiose three-flight staircase in front of it – bathroom and kitchen are in an additional building attached to the right side of the house. The first floor is copying the ground floor with the rectangular “hayet” and the four rooms around it. The main façade is symmetrical and includes a balcony which is a new feature for the Revival houses and appears to be coming from foreign influence. Strong external brick walls with thickness of 1.5 bricks as well as internal walls made out of the timber construction filled with adobe bricks are some of the main construction features of the house (Peev, 1960). It has a typical for the epoch façade finishing, but not as decorated as in the other example houses, as well as timber roof construction and floors. The interior is well decorated with wooden carving (Figure 15) but more decorative elements such as the “alafrangas” were removed during the renovation before it was used for a summer residence for Prince Ferdinand at the end of 19th and the beginning of 20th century. Since 1984 it poses as a permanent exhibition space for paintings of the famous Bulgarian painter Zlatiu Boyadziev (1903-1976).

Figure 15 House of Dr. Stoyan Chomakov - Interior (Personal archive)

### 2.5.3 House of Georgi Mavridi (Lamartine House) - (Къща на Георги Мавриди (Ламартинова къща))

Figure 16 House of Georgi Mavridi (Personal archive)

Located in the Old Town of Plovdiv the Lamartine house is named after the French poet Alphonse de Lamartine who used to stay there although it was built as a home of merchant Georgi Mavridi. It was built in 1829 and is one of the largest symmetrical houses in the Old Town. The house is situated on the northeastern slope of the hill “Djambaz tepe” on a corner plot with an irregular shape following the curvature of the streets. Therefore, the ground floor has an irregular shape which changes in the other storeys with the help of oriels and other protrusions. The street façade is 3-storey and the backyard façade is 2-storey because of the very steep terrain. A stone staircase leads to the first floor. Erected 1.65m above the yard ground level it has four big rooms flanking an elliptical salon. A three-flight staircase leads to the second floor which also has an elliptical salon (“hayet”) with higher ceiling than the four rooms around it which are slightly bigger than the ones on the first floor due to the oriels. Although it is an example of the symmetrical houses from the late Revival period, the house has only one absolutely symmetrical façade and the floor plans are not completely symmetrical as well due to the irregular shape of the plot it is built on (Peev, 1960). The interior is highly decorated with wood carving (doors, windows, ceilings, ballisters) and paintings as well as decorative niches called “alafrangas” (“алафранги“) typical for the Revival houses.

*Figure 17 House of Georgi Mavridi - construction (Scanned photo from Bulgarian national institute of cultural heritage)*

### 2.5.4 House of Dimitar Georgiadi – (Къща на Димитър Георгиади)

*Figure 18 House of Dimitar Georgiadi (Personal archive)*

The house was built in 1848 by the Rhodope master Hadzi Georgi Hadziyski for the rich merchant Dimitar Georgiadi. It is another typical example of the late Revival symmetrical house with a wide stone constructed cellar and ground floor and timber constructed upper floors and roof. The 760 m$^2$ house contains of a cellar, ground floor and two upper floors. The steep terrain is well used which is visible in the house plans creating spaces with different height (Figure 19). The cellar contains a water well, a rain water tank and spaces used for storage. Its construction is remarkable with the big supporting beams that were used - 30 by 35 cm (Peev, 1960). The ground floor contains an entrance vestibule and four rooms around it as well as the two-flight wooden staircase. The first and the second floors have the typical for the epoch “hayet” with an elliptical shape surrounded by four rooms but they are different in height. Kitchen, washing room and some other necessary spaces were put in an additional building in the yard.

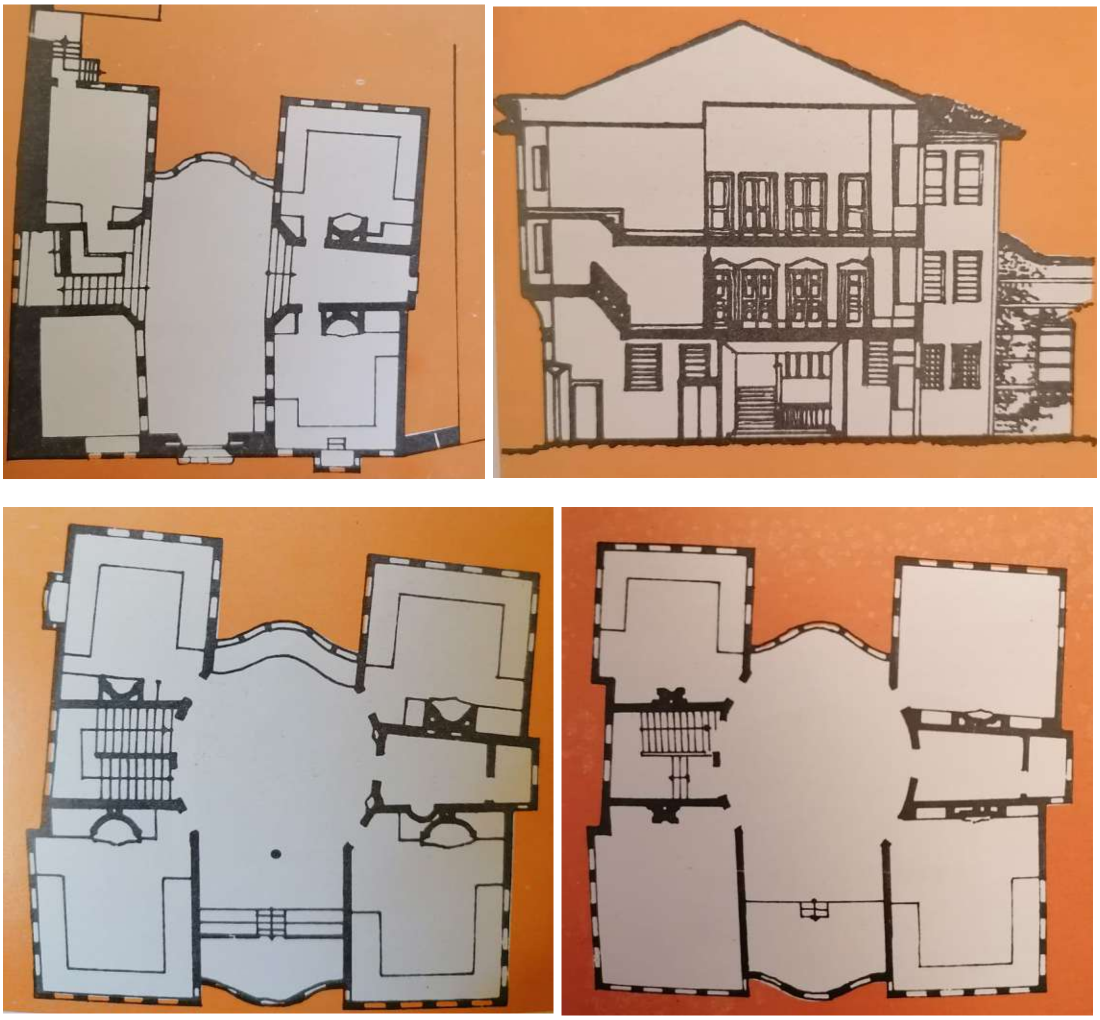


*Figure 19 Dimitar Georgiadi house plans - Ground floor (up left), Section (up right), First floor (down left), Second floor (down right) (Balabanova, 1978)*

The façade design is also very traditional for the time including wooden window frames with window covers attached to them, oriels supported by bended timber beams, roof eaves, painted plaster, etc (Figure 18, Figure 20). Oak beams were used for the timber construction connected with joints and iron nails (Figure 21).

*Figure 20 Backyard facade (Personal archive)*

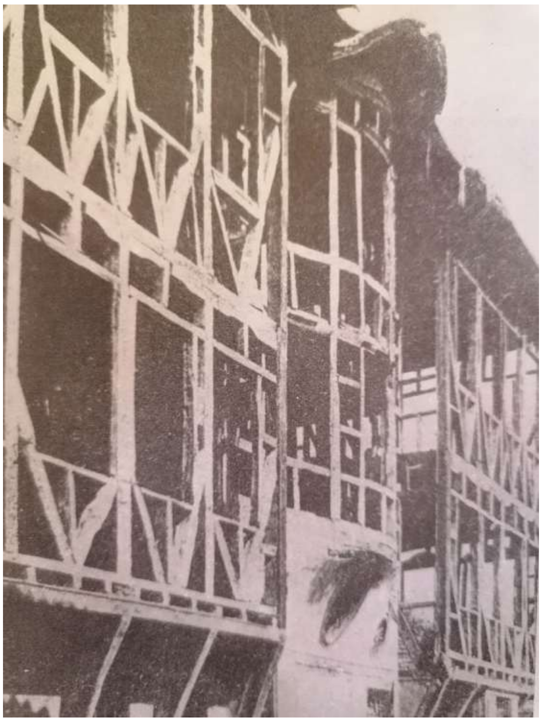


*Figure 21 Construction (Balabanova, 1978)*

The walls are built from small baked bricks (25.5/12/3.5 cm) in between the wooden beams and columns and the bricks are glued together using a solution made out of mud and straw. Some interior walls and the oriel walls were also filled with wooden slats as well to make the walls lighter. All walls have lime plaster finishes that have three layers: 2 or 3 cm clay and straw layer; 1.5 cm red mortar (slack lime with roofing tile powder) and the finest finishing layer of 3 to 5mm fine red mortar (Peev, 1960). The main beams and columns are not plastered, especially the corner ones, creating the typical Revival building style (Figure 18). The interior is beautifully decorated as in other houses of that period with wood carving, wall painting, decorative niches “alafranga” and interesting Baroque furniture (Figure 22).

*Figure 22 Interior (Personal archive)*

### 2.5.5 Kuyumdzieva house – (Куюмджиева къща)

*Figure 23 Kuyumdzieva house (Personal archive)*

The former home of the merchant Argir Kuyumdzioglu was built in 1847 on top of an old fortress wall and is a prominent example of Plovdiv's mid-19th century Baroque architecture. The house has inner patio with a garden, spreads over 1060 m$^2$ and has two main parts – the living area which is almost completely symmetrical with two pronounced axes of symmetry and an additional part – the southeastern wing that was built exactly next to the ancient fortress' gate. The main part of the house has a rectangular shaped salon ("hayet") that extends above the main entrance area ("portik") on the ground floor, a beautiful three-flight timber staircase and rooms flanking the salon. The east wing is connected to the floor with a corridor leading to the two rooms on each floor of the wing used for the house staff. The main façade looks over the garden and is completely symmetrical unlike the other two façades which follow the interior. The fourth façade is a party wall. Construction-wise the building is a typical example of the epoch – wide stone foundation and basement construction, timber walls filled with adobe bricks, timber roof and floors made out of thick oak beams with thickness up to 34 cm (Peev, 1960). The interior is very grandiose (Figure 24) – included are the typical for the period wooden carving decorations (ceilings, furniture), thick beech doors as well as painted walls highly decorated with floral motives.

*Figure 24 Kuyumdzieva house – interior (Personal archive)*

## 2.6 Constructions of the building elements

The Plovdiv Revival buildings are mostly 2-storey with high ceilings. The very hot summer and soft winter allowed for thin walls to be preferred by the builders. On the other hand, the Ottoman regime of insecurity necessitated high stone-fenced yards and thicker stone-masonry ground floors to create the feeling of security. Basements were not always possible because of the rocky terrain but whenever possible they were under the whole building.

### 2.6.1 Foundation and basement structures

The foundation of the buildings from that time are the same as the ground floors – thick stone masonry. Often the builders used mud or clay as adhesive for the stones and rarely they used lime mortar. In the basement usually thick oak columns support the upper walls (35 x 35 cm and more).

### 2.6.2 Floor slabs

Floor constructions were made from densely arranged beams reinforced with horizontal thick load-bearing oak beams called “taban”. The size of the beams range between 12 and 25 cm – most often they are 12/18 cm or 18/22 cm. The ground floor slab is made of compacted ground. The famous wooden carved ceilings were put directly on the construction of the upper floor. They are made of two layers of beech cladding – 1.5 - 2 cm thick bottom layer and a top layer of smooth beech boards (18 - 28 cm wide and 0.8 - 1 cm thick).

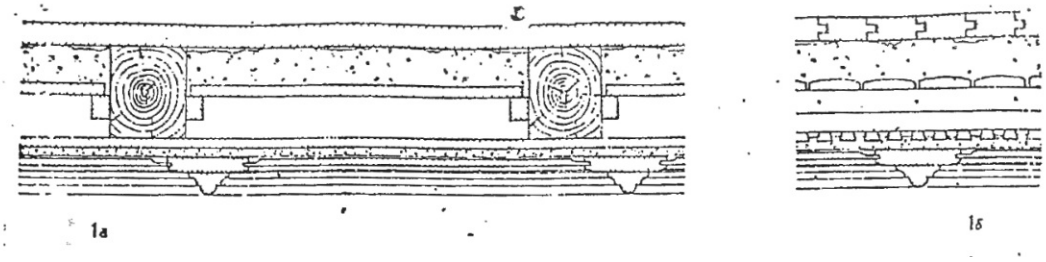


*Figure 25 Wooden floor construction with a decorative ceiling – sections (Popov, 1963)*

### 2.6.3 Interior walls

The interior walls in the basements were made from thick oak beams in order to support well the ceiling and the upper floors. The interior walls in the other floors were made from wooden skeleton structure with brick or adobe as well as broken clay shingles filling. On top of the filling the walls were covered in either clay with ray chaff mixture and lime plaster on top or with thin wooden planks (1 - 1.5 cm thick) and lime plaster on top. The bricks that were used are small (23 - 25 cm length, 11 - 12 cm width and 3 - 3.5 cm thickness) and not very durable and this is why they were not used for load-bearing structures by themselves. They are stacked together using clay and rye chaff adhesive mixture. The plaster used for the walls is wrongly called today “a-la-turka”. It usually consists of 2 or 3 layers on top of the adobe filled wall – 2 - 3 cm layer of clay and ray chaff mixture and 0.5 - 1 cm lime mortar which included slack lime, powdered clay or bricks and finely crushed hemp or ox hair, and a second layer of fine lime mortar and oil based paint on top (Peev, 1960).

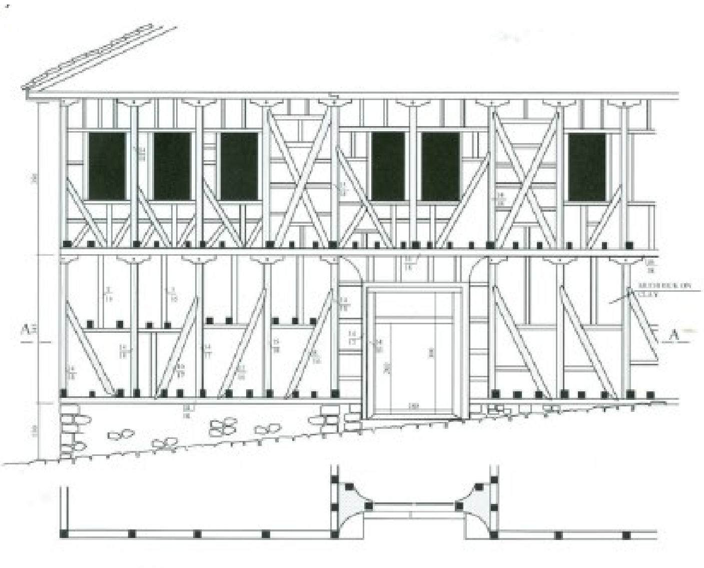


*Figure 26 Wooden structure of a house in Plovdiv (Peev, 1960)*

### 2.6.4 Exterior walls

Ground floor walls were built entirely or partly of river stone masonry with wooden skeleton in-between (usually ~70 cm thick). The stones were adhered with clay or mud mixture with rye chaff and were grouted with lime mortar. Rarely instead of river rocks coarse-grained rhyolite was used. The upper floors' exterior walls are the same as the interior walls (~20 cm walls with wooden structure).

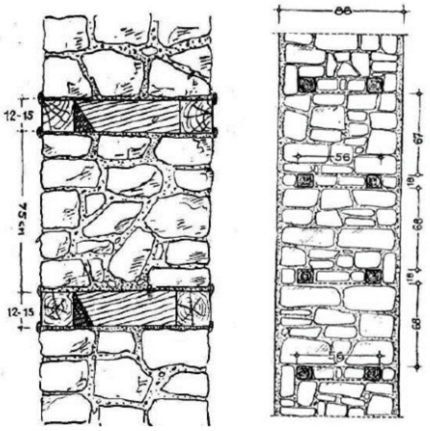


*Figure 27 Stone masonry with visible wooden girdles (left) and invisible wooden girdles (right) (Georgiev, 2015)*

### 2.6.5 Windows and doors

The window frames are thin (22 - 26 mm thickness and 40 mm width) and made from dry beech wood. Special slits in the frame allowed the window glass to be put directly on the frame without bonding material "madzhun". Doors were also made from dry beech wood and range between 3 and 5 cm in thickness.

### 2.6.6 Roof

The roofs are usually pitched but because of the mild climate and small amount of rain they have a very low slope (20-22%) (Peev, 1960). They are designed in such a way to create a wavy pattern and that, along with the low slope, creates an unsuitable for use underroof space. Their construction is also wooden as the other building elements and are covered in red clay shingles (~2 cm thick) laid on wooden planks on the beams or directly on the densely put beams using lime mortar. Typical sizes for the roofs' fir beams are 12/14 cm, 13/15 cm. The eaves of the roofs are not only for shading but exist because of structural necessity – the roof beams are connected to the walls in there. The ends of the eaves are sheeted with thin fir planks.

## 2.7 Insulation materials for optimization studies

The world's absolute dependance on energy has been a known fact for many years now but the distressing rate of energy consumption increase has led to many global initiatives who aim to decrease the amount of energy use which contributes to the greenhouse gas emissions and thus to global warming. The governments around the world are implementing measures in order to decrease those trends. As stated before, the building sector has been playing a major role in the energy consumption increase in the past decades. The historical building stock is quite a big percentage of the overall existing building stock which makes those buildings a big part of the possible energy use improvement. Despite this fact the national heritage buildings are more or less excluded from the energy efficiency regulations of Bulgaria and Europe overall (Ministry of regional development and public works, 2015). During the 20th century the interest in architectural heritage was focused solely on its cultural legacy and conservation. The vernacular architecture was mostly part of the cultural identity and a tourist attraction (El-borombaly and Prieto, 2015), but this trend is slowly changing given the recent interest in vernacular building and the sustainable building practices they were built with. Sustainability is a major necessity in buildings‘ renovations nowadays. The main goal of architectural refurbishment is to balance energy efficiency, thermal comfort and the national heritage conservation requirements providing maximum preservation and extending the life of the objects as much as possible for future generations (Martínez-Molina et al., 2016). One of the ways to maintain this balance is to refurbish historical buildings with the same type of materials that were used for their construction or others that would fit the sustainable building practices those buildings possess. For the purpose of this research three different types of thermal insulation is added to the buildings creating different cases that are compared in the Results section.

Considering the historical period in which the evaluated buildings were built and the materials that were used at that time two natural insulation materials were chosen – sheep wool and hemp wool (Georgiev, 2015). Both materials are extracted and used broadly around the territory of Bulgaria as part of the bulgarian agricultural livelihood thus making their use as an insulation material a sustainable choise – less production energy use, less transportation, etc . The choise of natural wool materials is in compliance with the necessity to put the insulation on the interior side of the building envelope elements due to the essential protection of the heritage buildings‘ facades. From the building physics‘ point of view putting the insulation on the inside often leads to condensation inside the building element which can not only lead to mold grow but can compromise the construction load-bearing capacity, especially when the building has a wooden skeleton which is the case in the examined buildings. Considering this fact, the sheep wool and the hemp have several advantages:

- They both have very good insulating properties with thermal conductivity (λ) of around 0.040 $W.m^{-1}.K^{-1}$
- Both sheep wool and hemp wool have the unique ability to absorb and release moisture from the surrounding air without compromising their effectiveness
- Wool is a natural, renewable resourse and is sustainable
- Wool is safe for people’s health and requires no special protection clothing when installed
- Wool fibres are breathable – they can release and absorb moisture without compromising its thermal performance (SheepWool Insulation Ltd., 2021). Its

hygroscopic properties allow the sheep wool to absorb up to 35% of the surrounding air's moisture

- Easy recycling process
- Work as a filter for harmful substances
- Wool does not settle even when damp due to its high elasticity
- „*Wool has a very high inflammation point of 560°C due to its high Nitrogen content of ~16%). It is self extinguishing because of its high Limiting Oxygen Index (LOI=25.2), which means to completely burn wool an oxygen content of 25.2% is necessary whereas air only has 21%*“ (SheepWool Insulation Ltd., 2021)

The disadvantages are that both hemp wool and sheep wool are about three times more expensive than mineral wool and sheep wool needs processing against insects.

The third used type of insulation material is EPS (expanded polystyrene) which was chosen for the sake of comparison between natural sustainable insulation materials as one of the most widespread contemporary materials. It also has a thermal conductivity (λ) of around 0.040 $W.m^{-1}.K^{-1}$ but is not as breathable and because of the condensation risk an air layer was implemented inside of the construction.

## 2.8 Simulation climate data

The weather conditions under which the simulations were carried out are generated from the available EnergyPlus weather file (epw) for Plovdiv, Bulgaria. The accurate description of the city's location plays a vital role for obtaining realistic results. Plovdiv is located at 42.13°N and 24.75°E, altitude 185 m and is in UTC +2.0 (EET). The climate, as stated before, is transitional subtropical continental with average daily temperatures between 6°C and 31°C throughout the year. The simulation model uses EnergyPlus weather file which contains information about Plovdiv's dry bulb temperature, dew point temperature, relative humidity, barometric pressure, wind speed and direction, solar radiation, illuminance levels and total sky cloud cover. The Meteonorm software (Meteotest AG, 2021) was used to visualize the current weather conditions and all data is available in Appendix D.

## 2.9 Bulgarian regulation requirements for residential buildings

The Bulgarian requirements for energy efficiency in buildings are stated mainly in Regulation №7 created in 2004 (Ministry of regional development and public works, 2015). The original document including all amendments (from 2009, 2015 and 2017) is the base that all new building projects as well as renovations must follow in order to be approved by the Ministry. The other two documents necessary for the purposes of this research are: Regulation №15 for technical rules and norms for construction and exploitation, heating energy (Ministry of regional development and public works and Ministry of energetics, 2016) as well as Regulation №49 for artificial lighting (Ministry of national health, 1976).

Since the building sector is constantly changing or adding to its requirements due to the continuous influence it has on the environment and considering the average age of the building stock in Europe, most buildings tend not to meet those requirements. However, a generous percentage of those buildings are still in use and often cannot provide the necessary comfort to its inhabitants even with an enormous energy consumption. It is proven that temperature has a greater influence on the subjective feeling of comfort than a contaminated environment or loud noise (Chobanov, 2017). In addition to this in most buildings around 30% of the primary energy consumption comes from heating and cooling necessities. Thus, all new buildings, reconstructions, refurbishments, etc. are striving to provide the best possible energy efficiency solely covered by the building envelope.

Regulation №7 (Ministry of regional development and public works, 2015) includes suggestions for the building constructions to follow:

- Buildings need to be positioned and oriented so that they obtain optimal solar gains as well as provide the prevention of overheating and damage from water, plants, animals, chemical influences, etc.
- Buildings need to not pose threat for its inhabitants' health or hygiene as well as for the environment around the building. They also need to provide the necessary comfort providing the microclimate parameters don't exceed the one stated in the regulation
- The energy consumption of the building needs to be minimal
- Buildings need to be isolated with thermal and sound insulation as well as against unacceptable influence of vibrations according to their location, use, and climatic conditions

- Buildings need to be energy efficient, exhausting as little energy as possible during their construction, exploitation and demolition
- Buildings need to be compliant with the possibilities of exploitation of solar energy when this is possible and economically appropriate

In order to determine the primary energy consumption of buildings an energy balance is calculated. To create the energy balance, a thermal transmittance calculation (U-value [$W.m^{-2}.K^{-1}$]) calculation is necessary. The reference values for it are given in the following table:

*Table 2 Reference values of thermal transmittance coefficient through opaque building elements (Ministry of regional development and public works, 2015)*

| | Type of building element | U-value [$W.m^{-2}.K^{-1}$] | |
|---|---|---|---|
| | | Buildings with average inside temperature $\Theta_i \geq 15°C$ | Buildings with average inside temperature $\Theta_i < 15°C$ |
| 1 | External walls | 0.28 | 0.35 |
| 2 | Interior walls between heated and unheated spaces with a temperature difference of 5°C or more | 0.50 | 0.63 |
| 3 | External walls of heated spaces bordering the ground | 0.60 | 0.75 |
| 4 | Floor slab above an unheated cellar | 0.50 | 0.63 |
| 5 | Floor to ground of a heated space in a building without a cellar | 0.40 | 0.50 |
| 6 | Floor to ground of a heated cellar | 0.45 | 0.56 |
| 7 | Floor of a heated space bordering outside air space (above entrances, oriels, etc.) | 0.25 | 0.32 |
| 8 | Wall, ceiling or floor with built-in heating bordering outside air space or the ground | 0.40 | 0.50 |
| 9 | Flat roof without air space or with an air space less than 30cm thick; Pitched roof with a heated livable space underneath | 0.25 | 0.32 |
| 10 | Ceiling of unheated flat roof with a more than 30cm thick air space; Ceiling of unheated, ventilated or unventilated pitched roof, with or without vertical enveloping elements under the roof | 0.30 | 0.38 |
| 11 | External door | 2.20 | 2.75 |
| 12 | Door bordering unheated space | 3.50 | 4.38 |

The reference values for the transparent enveloping elements are given in the following table:

*Table 3 Reference values of thermal transmittance coefficient through transparent building elements (Ministry of regional development and public works, 2015)*

| | Type of element | $U_w$-value [W.m$^{-2}$.K$^{-1}$] |
|---|---|---|
| 1 | External windows, glass doors or walls with PVC frames, roof windows with PVC frames | 1.4 |
| 2 | External windows, glass doors or walls with timber frames, roof windows with timber frames | 1.6/1.8 |
| 3 | External windows, glass doors or walls with aluminum frames with interrupted thermal bridge | 1.7 |
| 4 | Glass façade systems | 1.75/1.9 |

The thermo-physical characteristics of different construction materials used in the example buildings of this research are taken from Annex 4 of Regulation №7.

Considering the microclimate building comfort calculation values are determined in Annex 12 of Regulation №7. The values for residential buildings are shown in the following table:

*Table 4 Calculation parameters of microclimate in residential buildings according to БДС CR 1752 and БДС EN 15251 (Ministry of regional development and public works and Ministry of energetics, 2016)*

| Type of building | Inhabitants number.m$^{-2}$ | Category of environment comfort* | Temperature | | Sound pressure level | Fresh air debit |
|---|---|---|---|---|---|---|
| | | | Summer | Winter | | |
| | | | °C | °C | db(A) | m$^{3}$.s$^{-1}$.m$^{-2}$ |
| Residential buildings | 1.2 | I | - | 22±1 | 30 | 0.00049 |
| | | II | - | 22±2 | 40 | 0.00042 |
| | | III | - | 22±3 | 45 | 0.00035 |
| | | IV | - | <19 | 45 | 0.00030 |

* Categories of interior environment quality:

I – High expectation level: Spaces for people with specific needs (disabled, elderly, etc.) – PMV (Predicted mean vote) -0.2 < PMV < 0.2; PMD (predicted % of dissatisfied) PMD < 6%

II – Normal expectation level: Should be used for new or renovated buildings
-0.5 < PMV < 0.5; PMD < 10%

III – Moderate expectation level: Should be used for existing buildings
-0.7 < PMV < 0.7; PMD < 15%

IV – Category possible only for a short-term use of the building PMV < -0.7 or PMV > 0.7; PMD > 15%

The classification of residential buildings by energy demand according to Bulgarian Regulation №7 is shown in the following figure:

| Клас | EPmin, kWh/m$^2$ | EPmax, kWh/m$^2$ | ЖИЛИЩНИ СГРАДИ |
|---|---|---|---|
| A+ | < | 48 | A+ |
| A | 48 | 95 | A |
| B | 96 | 190 | B |
| C | 191 | 240 | C |
| D | 241 | 290 | D |
| E | 291 | 363 | E |
| F | 364 | 435 | F |
| G | > | 435 | G |

*Figure 28 Building classes according to their annual primary energy demand (Ministry of regional development and public works, 2015)*

## 2.10 Dynamic simulation parameters

This study is based on the evaluation of the thermal and visual comfort of five example buildings, all located in Plovdiv, Bulgaria. Five different simulation cases were performed for each of the five buildings. They are as follows:

- Base case – all buildings were simulated in their current condition
- Case EEW – all buildings were simulated with energy efficient windows instead of the current single pane windows

- Case SW – all buildings were simulated with sheep wool insulated building envelope
- Case H – all buildings were simulated with hemp wool insulated building envelope
- Case EPS – all buildings were simulated with EPS insulated building envelope

All houses' basic building geometry parameters are stated in Table 5 and all other input parameters are stated in Table 6, Table 7, Table 8, Table 9 and Table 10.

*Table 5 General geometry parameters of the buildings*

| | House Hindlyan | Dr. St. Chomakov house | Georgi Mavridi (Lamartine) house | Dimitar Georgiadi house | Kuyumdzieva house |
|---|---|---|---|---|---|
| Country, City | Plovdiv, Bulgaria | | | | |
| Number of floors | 2 heated floors | 2 heated floors and an unheated basement | 3 heated floors | 3 heated floors | 2 heated floors and an unheated basement |
| Construction period | Late 19th – early 20th century | | | | |
| Wall construction | • River rocks masonry ground floor<br>• Wooden skeleton construction with an adobe filling and straw and clay cover for the other floors | | | | |
| Gross heated area | 609.65$m^2$ | 690.76$m^2$ | 583.19 $m^2$ | 756.47 $m^2$ | 1053.29 $m^2$ |
| Gross heated volume | 2053.38 $m^3$ | 2583.35 $m^3$ | 1843.71 $m^3$ | 2668.84 $m^3$ | 4169.04 $m^3$ |
| Transparent building elements area | 97.04$m^2$ | 69.25 $m^2$ | 100.80 $m^2$ | 168.78 $m^2$ | 172.38 $m^2$ |
| Opaque building elements area | 1299.06$m^2$ | 1331.42 $m^2$ | 989.88 $m^2$ | 1197.49 $m^2$ | 1856.43 $m^2$ |

*Table 6 Internal conditions plugged into the Honeybee* ***setEPZoneLoads*** *and* ***EnergySymPar*** *components*

| Internal conditions for all cases – heated zone parameters (roof zone) | |
|---|---|
| Infiltration rate per area façade ($m^3.s^{-1}.m^{-2}$) | 0.00035 |
| Equipment load per area ($W.m^{-2}$) | 3 (0) |
| Lighting density per area ($W.m^{-1}$) | 7 (0) |
| Number of people per area ($ppl.m^{-2}$) | 0.05 (0) |
| Zone program | Midrise apartment |
| Natural ventilation type | Window natural ventilation – Wind driven cross ventilation<br>(No natural ventilation) |
| Fraction of glazing area operable | 1 |
| Fraction of glazing height operable | 1 |
| Stack discharge coefficient | 0.65 |
| Terrain | 1 - Suburbs |

The infiltration rate per area façade has been chosen according to БДС CR 1752 and БДС EN 15251 (Ministry of regional development and public works and Ministry of energetics, 2016) stated in Table 4. It is the equivalent of approximately 0.6 ACH (air changes per hour).

*Table 7 Zone thresholds plugged into the Honeybee* ***setEPZoneThresholds*** *and* ***setEPNatVent*** *components*

| Zone Thresholds | |
|---|---|
| Thermostat cooling setpoint | 26 °C |
| Thermostat heating setpoint | 18 °C |
| Maximum relative humidity | 50% |
| Minimum relative humidity | 40% |
| Minimum indoor temperature for natural ventilation | 22 °C |
| Maximum indoor temperature for natural ventilation | 25 °C |
| Minimum outdoor temperature for natural ventilation | 22 °C |
| Maximum outdoor temperature for natural ventilation | 25 °C |

*Table 8 Schedules plugged into the Honeybee **setEPZoneSchedules** components*

| Schedules | |
|---|---|
| Ventilation schedule | Dry bulb outdoor temperature >22 °C = 1<br>Dry bulb outdoor temperature <22 °C = 0 |
| Occupancy schedule – weekday | 00:00 – 06:00 = 1; 06:00 – 11:00 = 0.5<br>11:00 – 13:00 = 1; 13:00 – 18:00 = 0.5<br>17:00 – 24:00 = 1 |
| Occupancy schedule – weekend | 00:00 – 06:00 = 1; 06:00 – 11:00 = 0.5<br>11:00 – 24:00 = 1; |
| Occupancy schedule – basements - weekday | 00:00 – 06:00 = 0; 06:00 – 11:00 = 0.5<br>11:00 – 13:00 = 0; 13:00 – 18:00 = 0.5<br>17:00 – 24:00 = 0 |
| Occupancy schedule – basements - weekend | 00:00 – 06:00 = 0; 06:00 – 11:00 = 0.5<br>11:00 – 24:00 = 0; |

The monthly ground temperatures which were considered for the simulations are stated in Table 9.

*Table 9 Ground temperatures input into the Honeybee **EnergySymPar** components*

| | |
|---|---|
| January | 18°C |
| February | 18°C |
| March | 18°C |
| April | 20 °C |
| May | 20 °C |
| June | 21 °C |
| July | 22 °C |
| August | 24 °C |
| September | 24 °C |
| October | 19 °C |
| November | 18°C |
| December | 18°C |

Zoning is a vital part of any building performance evaluation. The zoning of all five example buildings is shown in Appendix A.

In order to perform the simulations in most accurate way the thermal properties of the building constructions and the materials they consist of are necessary. EnergyPlus (International collaboration team, 2020) requires width, thermal conductivity, density and specific heat capacity to be plugged in the material component in order to create new materials. All those parameters are shown in tables for each building's five cases in Appendix B.

The building elements' thermal transmittance (U-value) is regulated by the Bulgarian ministry of regional developments and public works and the reference values for transparent and opaque building elements are shown in Table 2 and Table 3. The following table shows the U-values of the buildings' base case and whether it complies with the current regulations.

*Table 10 U-values of construction elements in all cases*

| | Thermal transmittance (U-value) [W.m$^{-2}$.K$^{-1}$] | | | | |
|---|---|---|---|---|---|
| | Base Case | EEW | SW | HEMP | EPS |
| External wall – ground floor | 2.50 | 2.50 | 0.39 | 0.40 | 0.41 |
| External wall – upper floors | 4.06 | 4.06 | 0.42 | 0.43 | 0.44 |
| External wall – basement (where existing) | **2.84*** | **2.84** | **2.84** | **2.84** | **2.84** |
| Floor to ground | **1.33** | **1.33** | **0.35** | **0.36** | **0.37** |
| Floor/Ceiling | **0.21** | **0.21** | **0.21** | **0.21** | **0.21** |
| Exposed floor | **0.21** | **0.21** | **0.30** | **0.31** | **0.31** |
| Floor to unheated basement (where existing) | **0.21** | **0.21** | **0.30** | **0.31** | **0.31** |
| Ceiling to roof space | **0.22** | **0.22** | **0.31** | **0.32** | **0.33** |
| Roof | **0.16** | **0.16** | **0.16** | **0.16** | **0.16** |
| Roof ground floor zones | **0.16** | **0.16** | **0.24** | **0.24** | **0.25** |
| Window | 4.8 | **1.48** | **1.48** | **1.48** | **1.48** |

*The U-values complying with the current regulations are shown in bold.

The same models were used for the daylight simulations. A test point grid surface was created 0.75 m above all floor surfaces with a 0.05 m distance between the grid points. All simulations use a uniform sky model and were produced for the summer and winter solstices and autumnal and vernal equinoxes as well as a representative day of each month at noon. The type of simulation results requested are illuminance (lux) and daylight factor (%).

# 3 RESULTS

In this chapter all significant simulation results are presented for both the thermal and the visual evaluation of the five example buildings. With the help of graphs and charts a comparison between all example buildings in their base case and four optimization scenarios is made and later on discussed in Chapter 4. The chapter is organized in sections presenting the most significant parameters for thermal comfort, precisely temperature, relative humidity, thermal demand, transmission losses, air change losses, solar gains, internal gains. The possibility of overheating during the summer months is also evaluated and the results are presented in another part of this chapter. Chapter 3.9 introduces the visual evaluation of the buildings with the help of important parameters (illuminance and daylight factor) expressing the natural lighting of all discussed buildings.

## 3.1 Temperature

The air temperature is a key factor for obtaining thermal comfort in a building. People usually link thermal comfort to air temperature and although comfort is subjective and not solely influenced by temperature, it is essential for evaluating the thermal performance of a building. Figure 29 to Figure 33 illustrate the monthly air temperatures in each of the five cases of the example buildings.

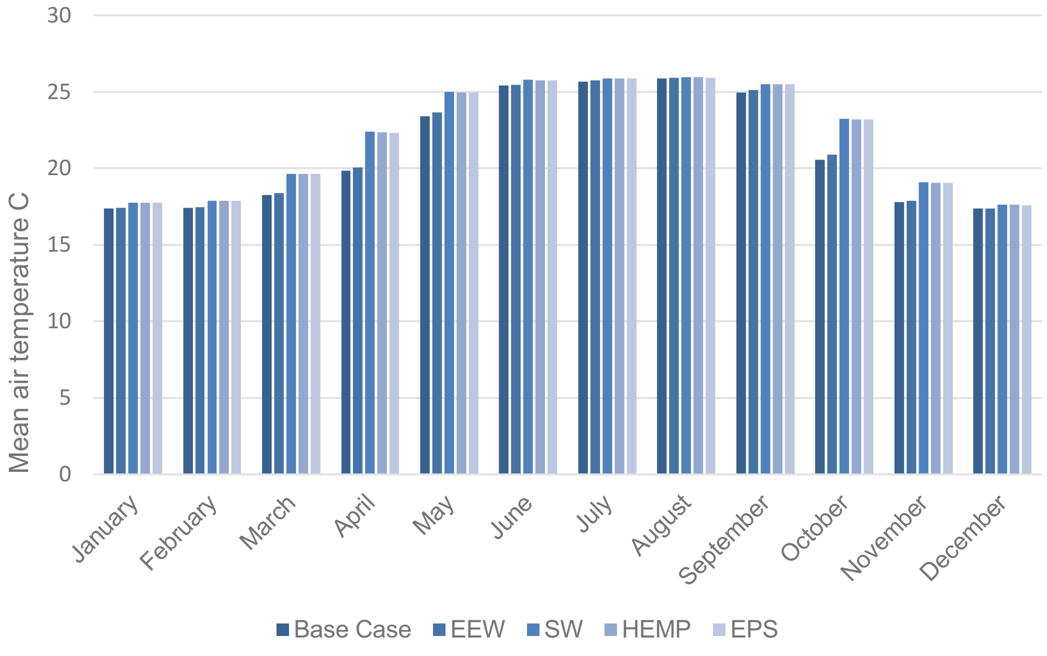


*Figure 29 Monthly air temperatures of House Hindlyan*

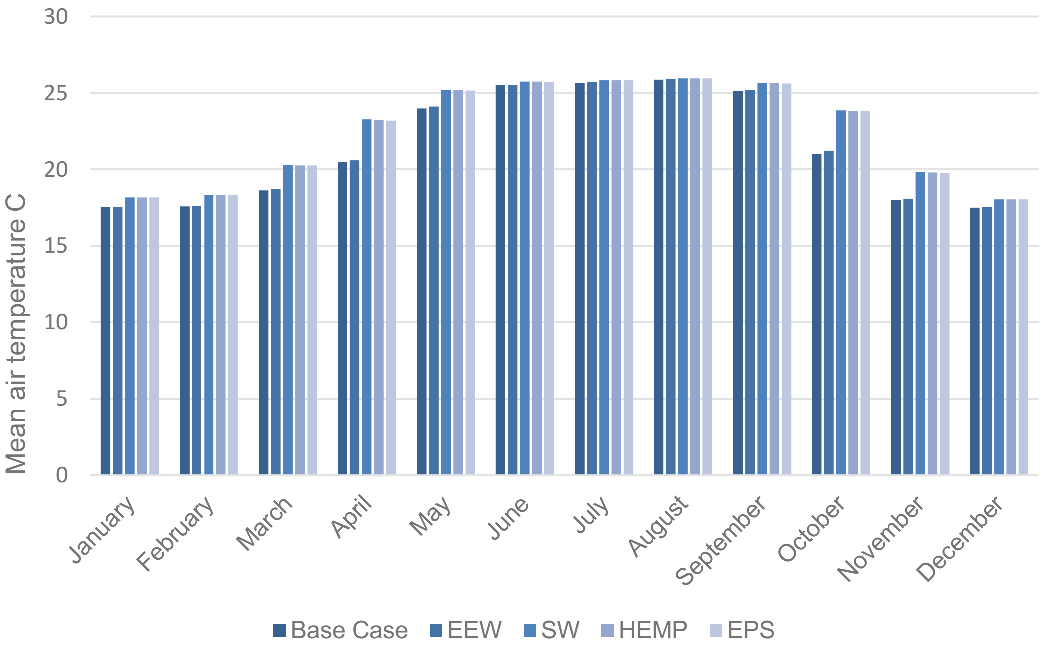


*Figure 30 Monthly air temperatures of House of Dr. Stoyan Chomakov*

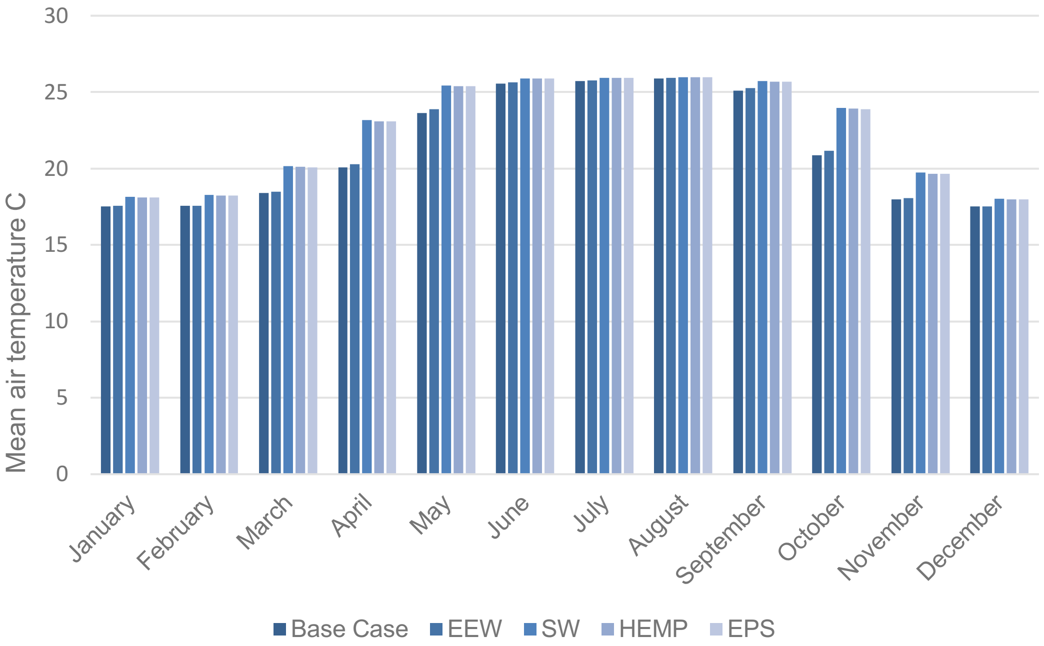


*Figure 31 Monthly air temperatures of House of Georgi Mavridi (Lamartine House)*

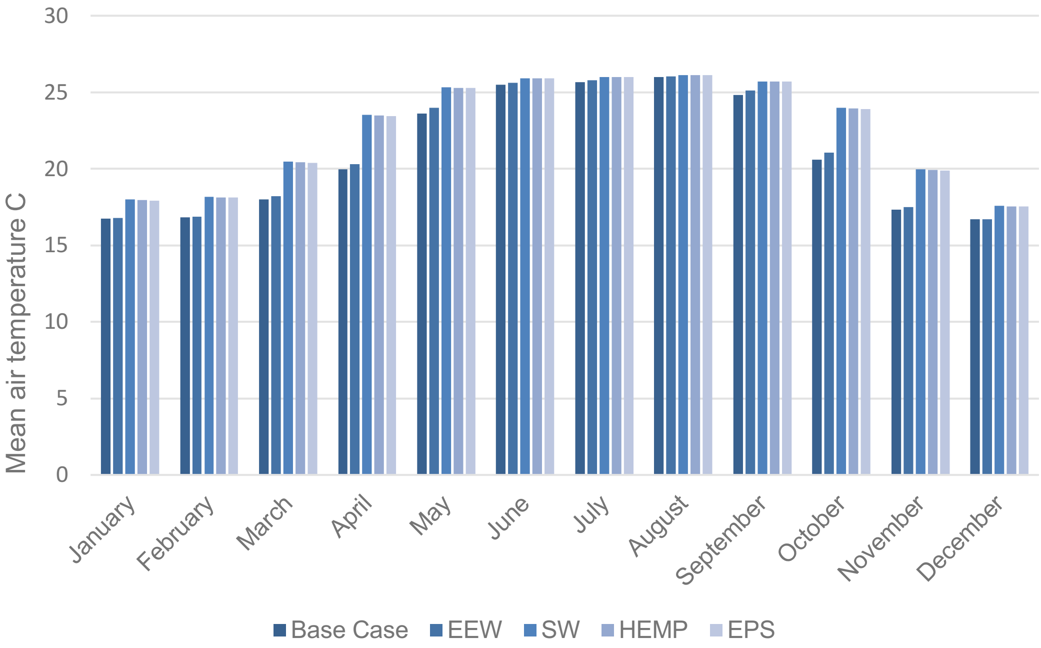


*Figure 32 Monthly air temperatures of House of Dimitar Georgiadi*

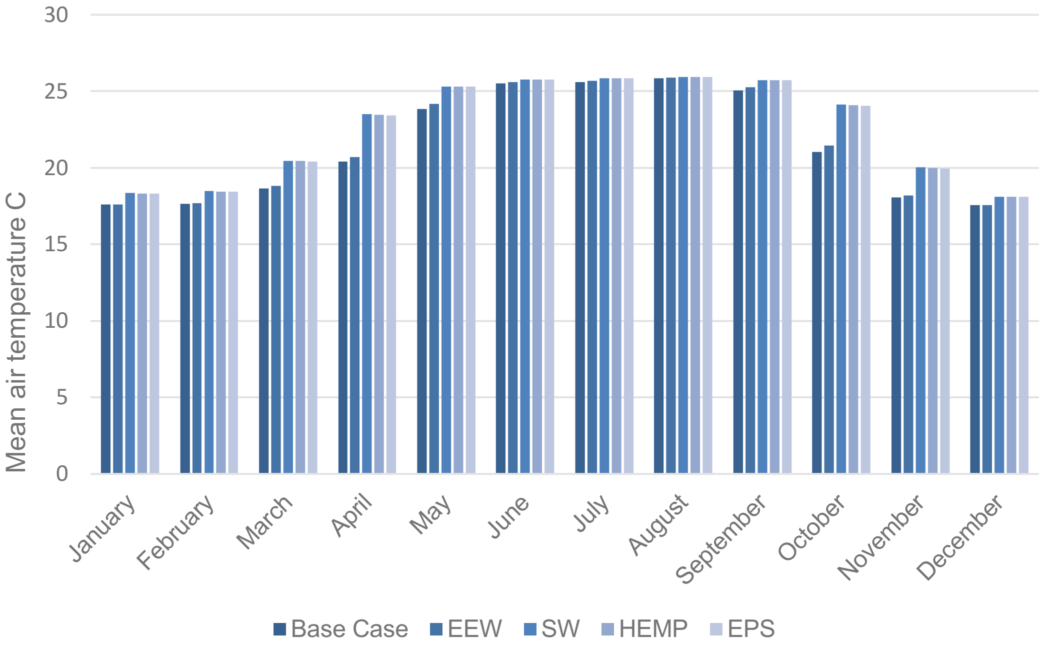


*Figure 33 Monthly air temperatures of Kuyumdzieva house*

“*Operative temperature is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed*” (ASHRAE, 2020). Operative temperature is used for analyzing the thermal comfort in buildings as shown in ASHRAE Standard 55's psychrometric chart (ASHRAE, 2020). Figure 34 to Figure 38 show the monthly operative temperature values in each building's five cases.

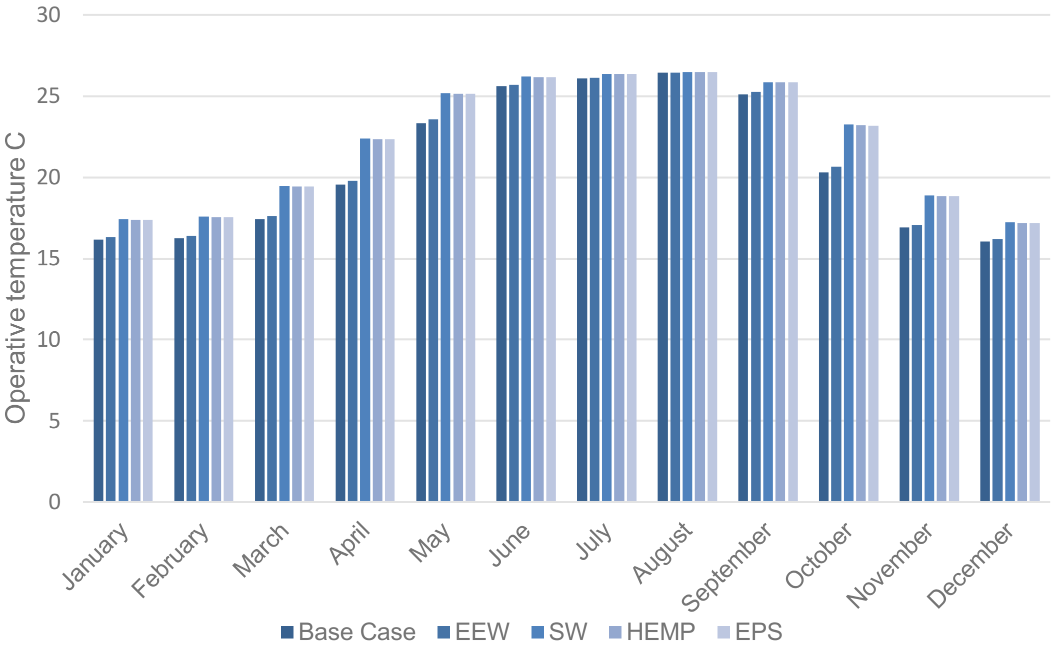


*Figure 34 Monthly operative temperatures of House Hindlyan*

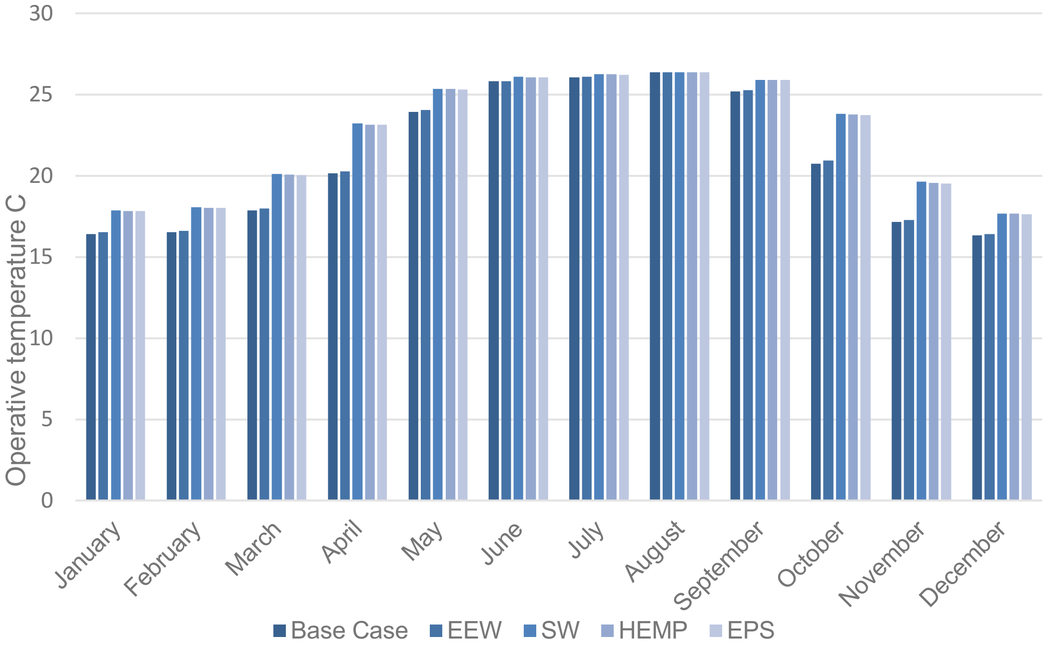


*Figure 35 Monthly operative temperatures of House of Dr. Stoyan Chomakov*

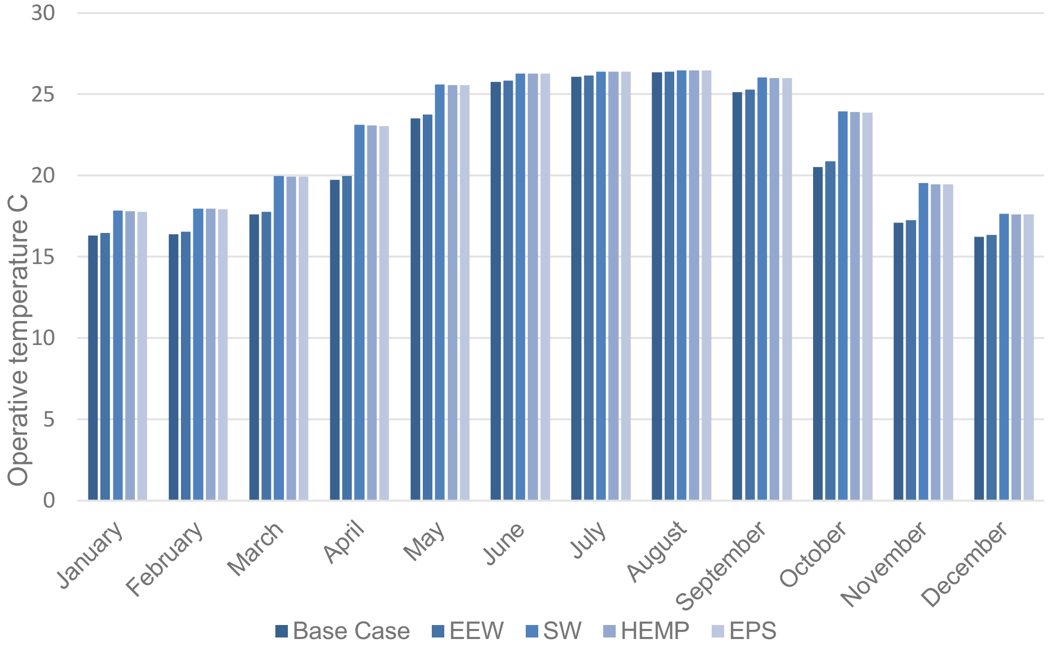


*Figure 36 Monthly operative temperatures of House of Georgi Mavridi (Lamartine House)*

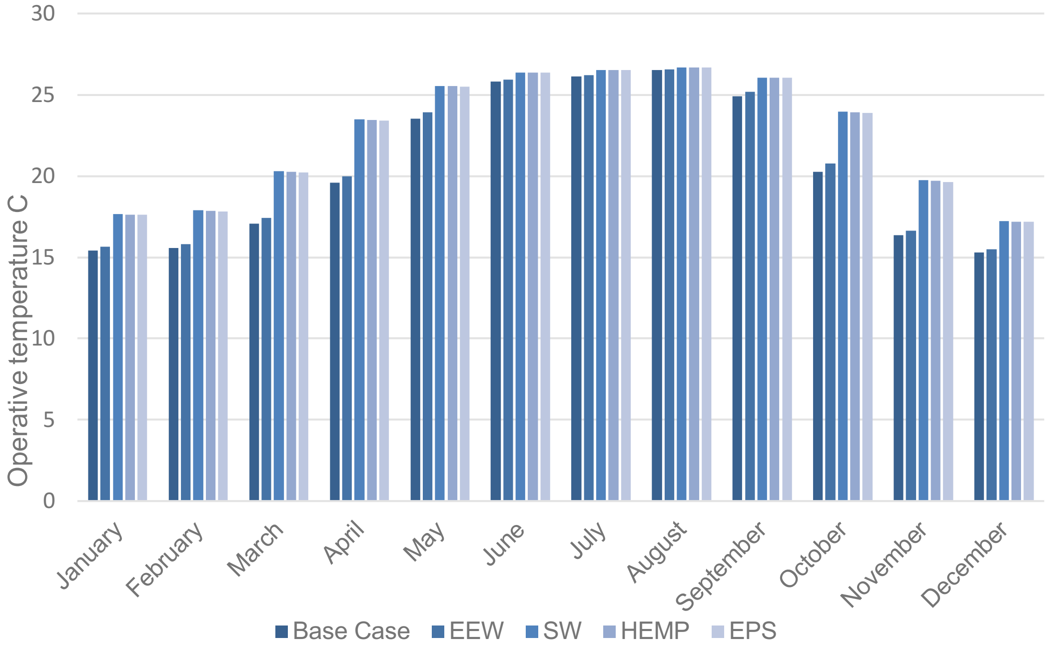


*Figure 37 Monthly operative temperatures of House of Dimitar Georgiadi*

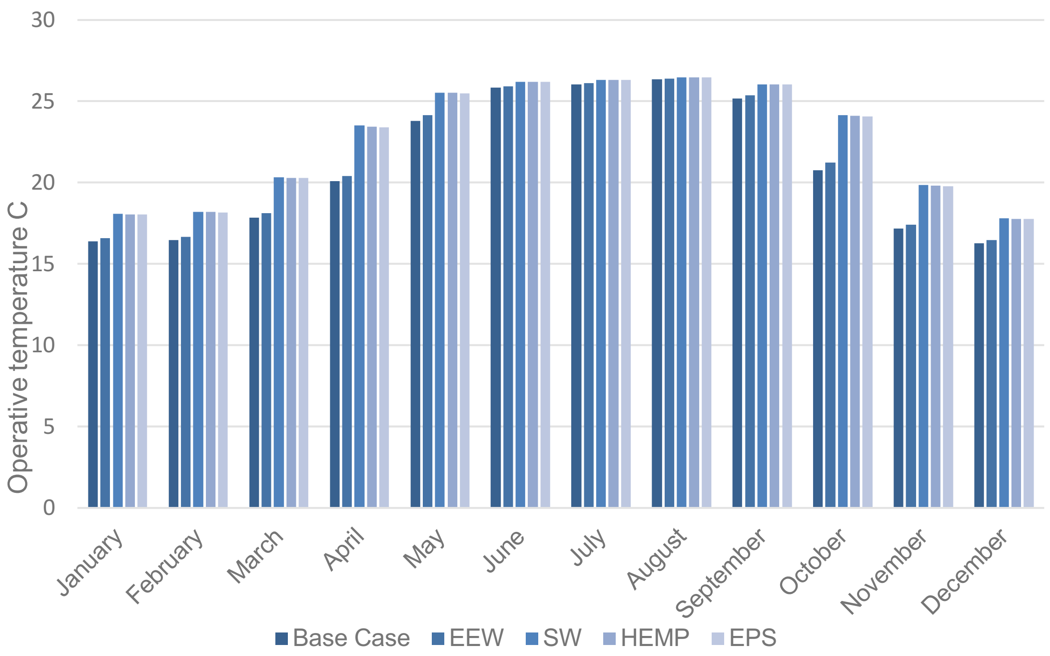


*Figure 38 Monthly operative temperatures of Kuyumdzieva house*

## 3.2 Relative humidity

Relative humidity is the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor the air can contain at a certain temperature. Very high humidity blocks the evaporation of sweat which is the main human heat reduction process, making the humidity levels very important, especially in warmer environments. Figure 39 to Figure 43 shows the results of relative humidity levels in each of the examined buildings' five cases.

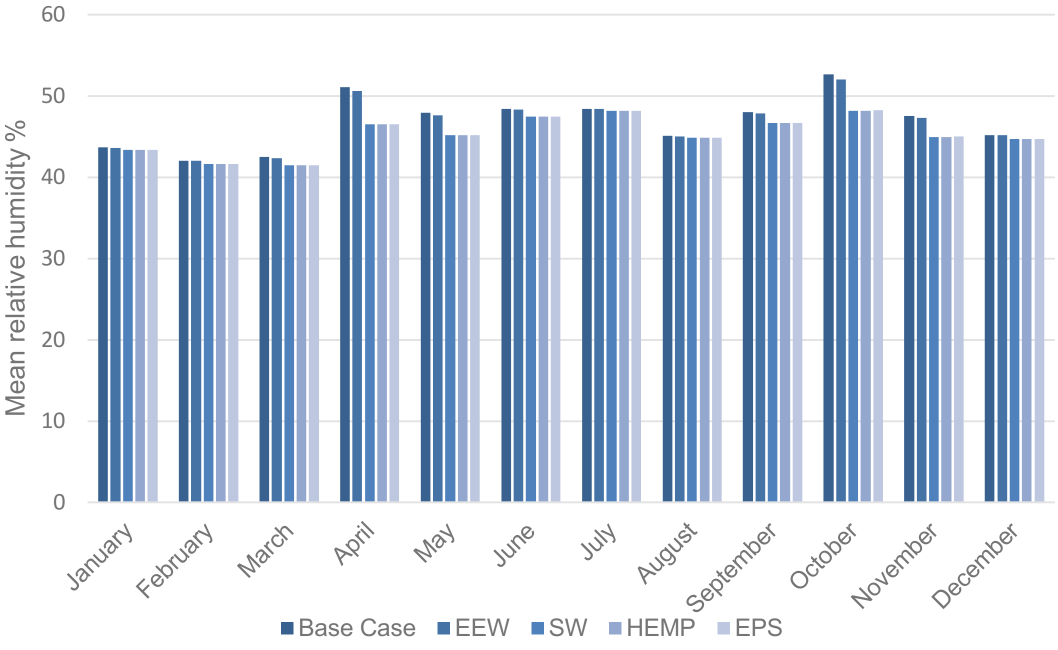


*Figure 39 Monthly relative humidity levels of House Hindlyan*

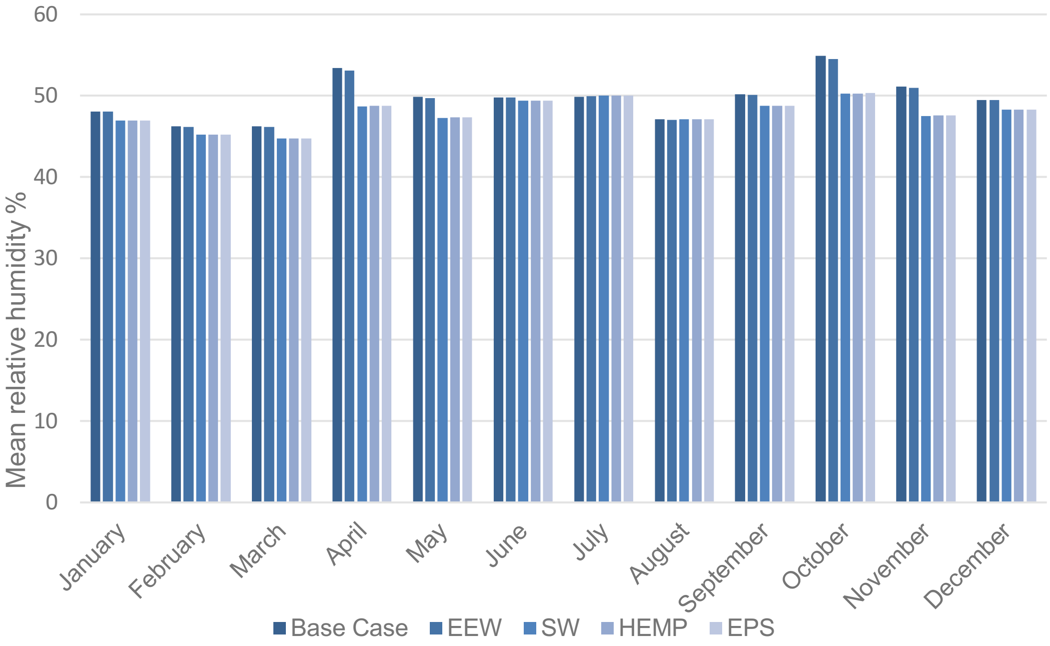


*Figure 40 Monthly relative humidity levels of House of Dr. Stoyan Chomakov*

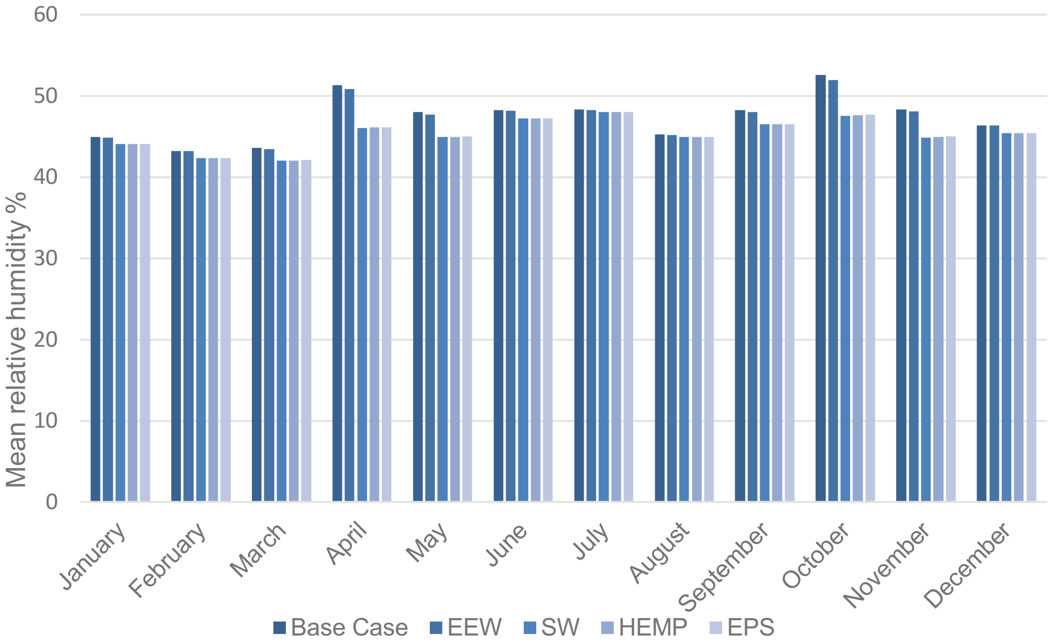


*Figure 41 Monthly relative humidity levels of House of Georgi Mavridi (Lamartine House)*

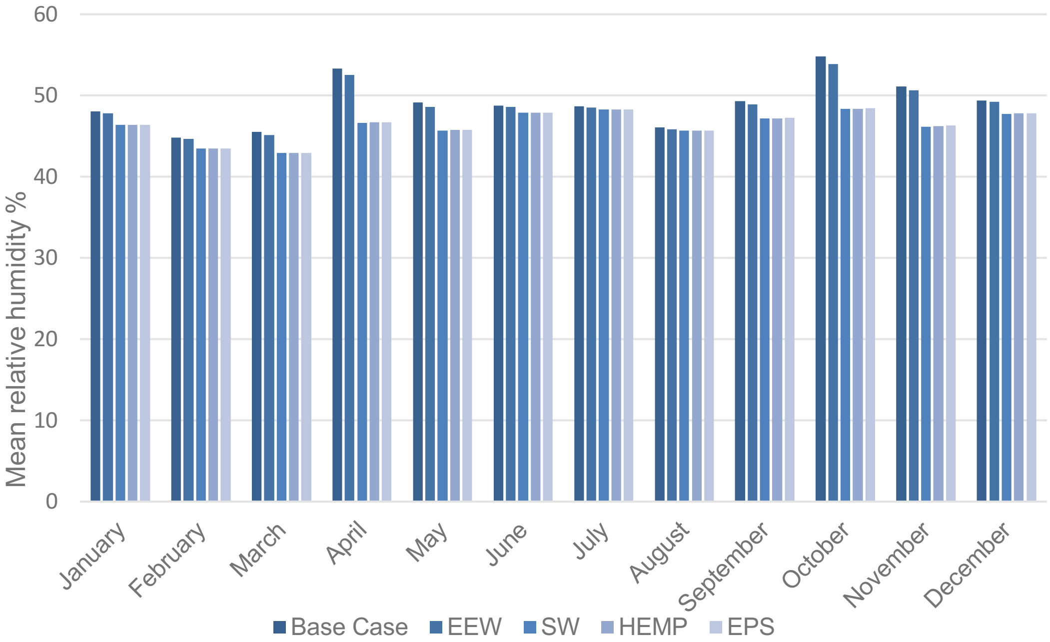


*Figure 42 Monthly relative humidity levels of House of Dimitar Georgiadi*

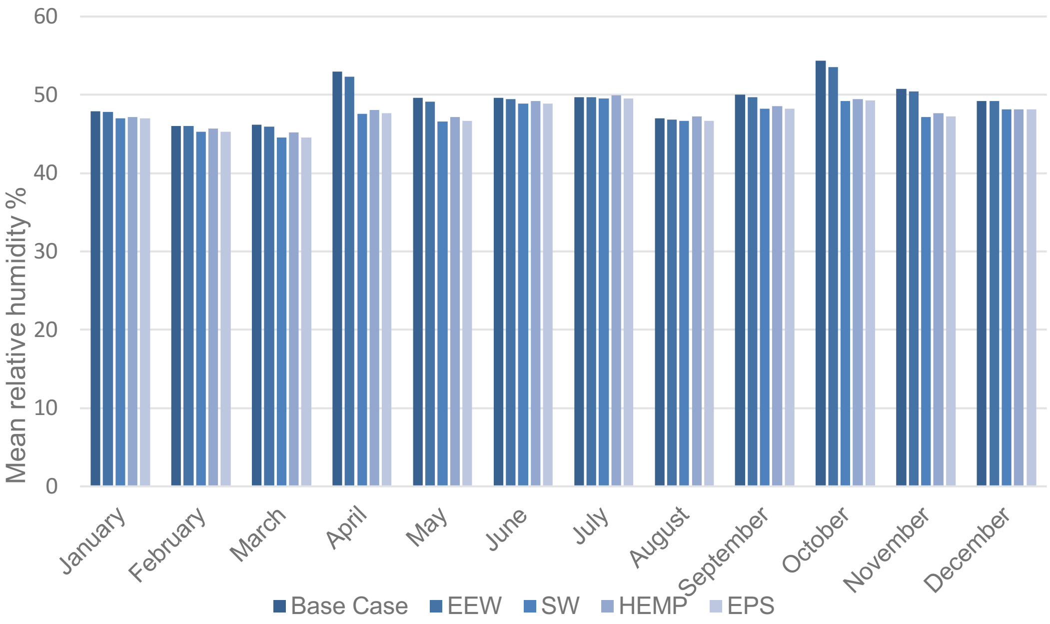


*Figure 43 Monthly relative humidity levels of Kuyumdzieva house*

## 3.3 Annual heating load

The annual heating load represents the amounts of heat energy necessary for a building to obtain comfortable indoor environment. Figure 44 to Figure 48 represent the simulation results for each building's five cases for the annual heating load as well as the difference (%) the four optimized cases made in the amount of heating load compared to the base case.

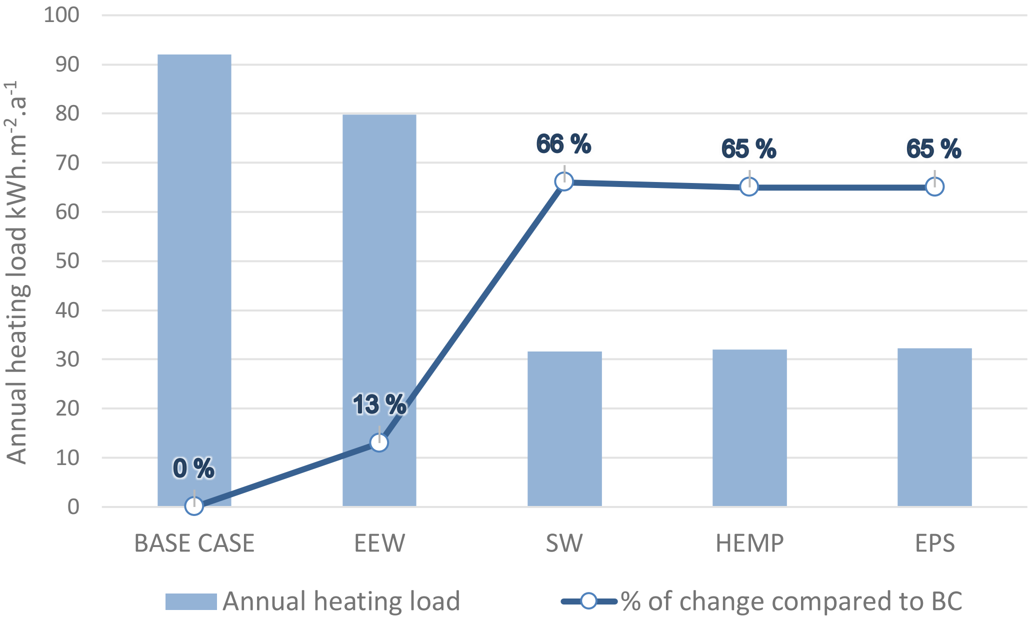


*Figure 44 Annual heating load of House Hindlyan*

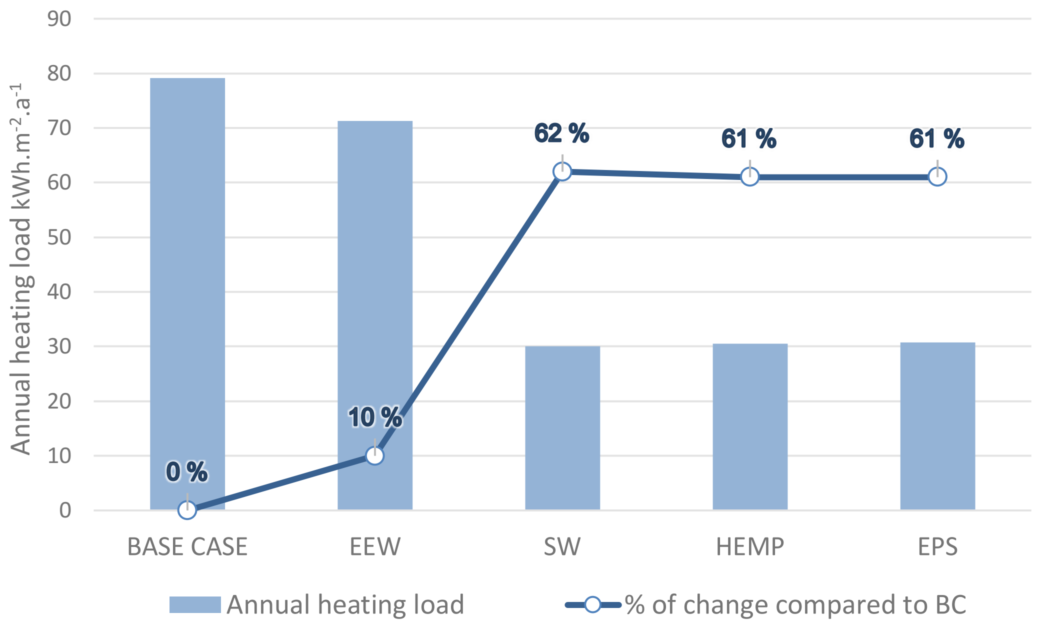


*Figure 45 Annual heating load of House of Dr. Stoyan Chomakov*

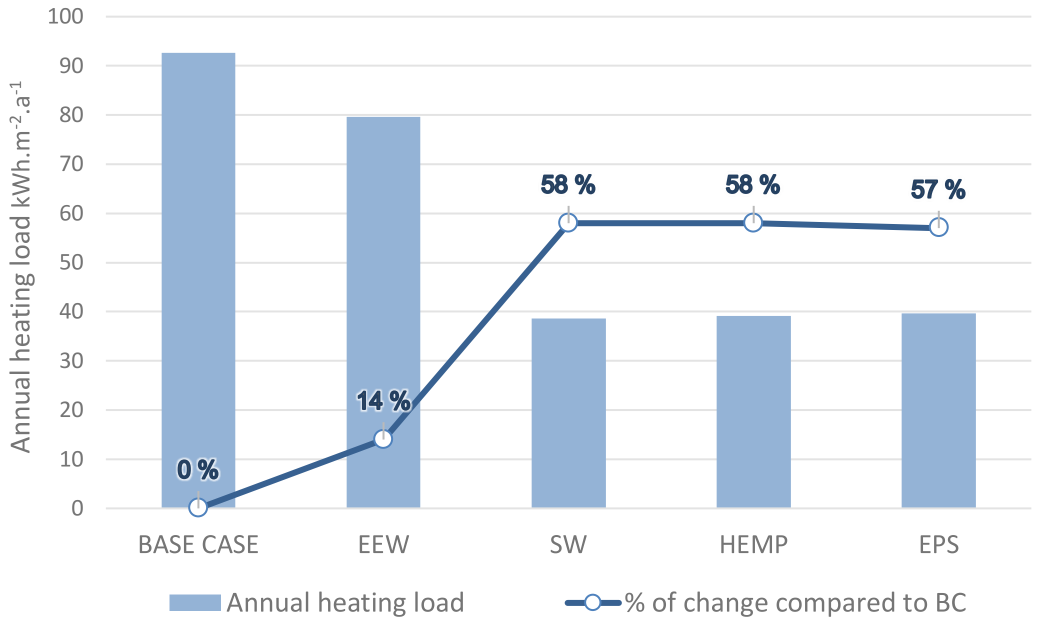


*Figure 46 Annual heating load of House Lamartine*

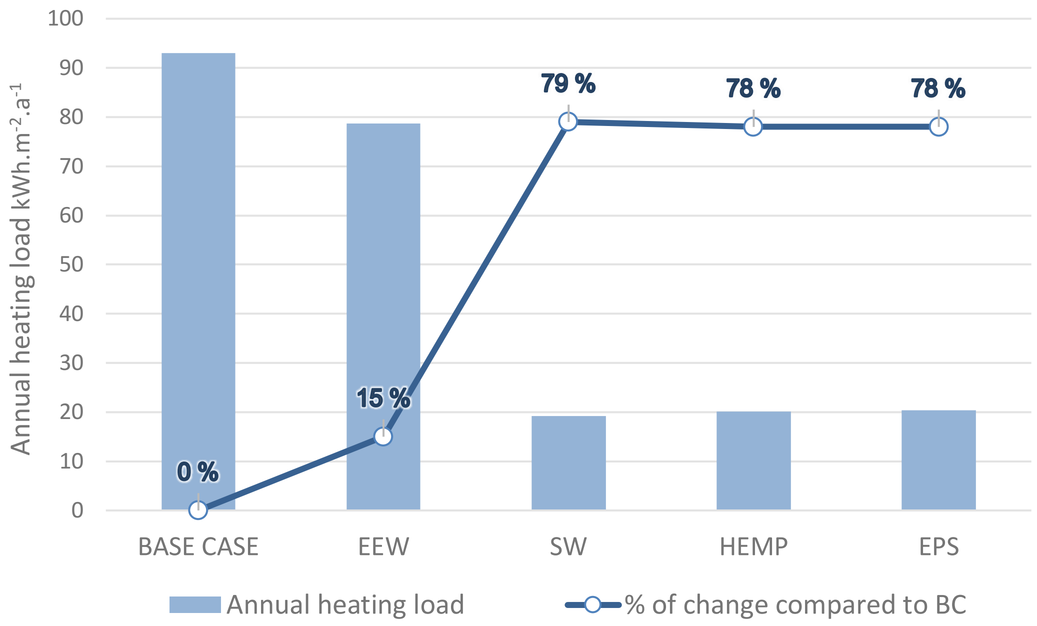


*Figure 47 Annual heating load of House of Dimitar Georgiadi*

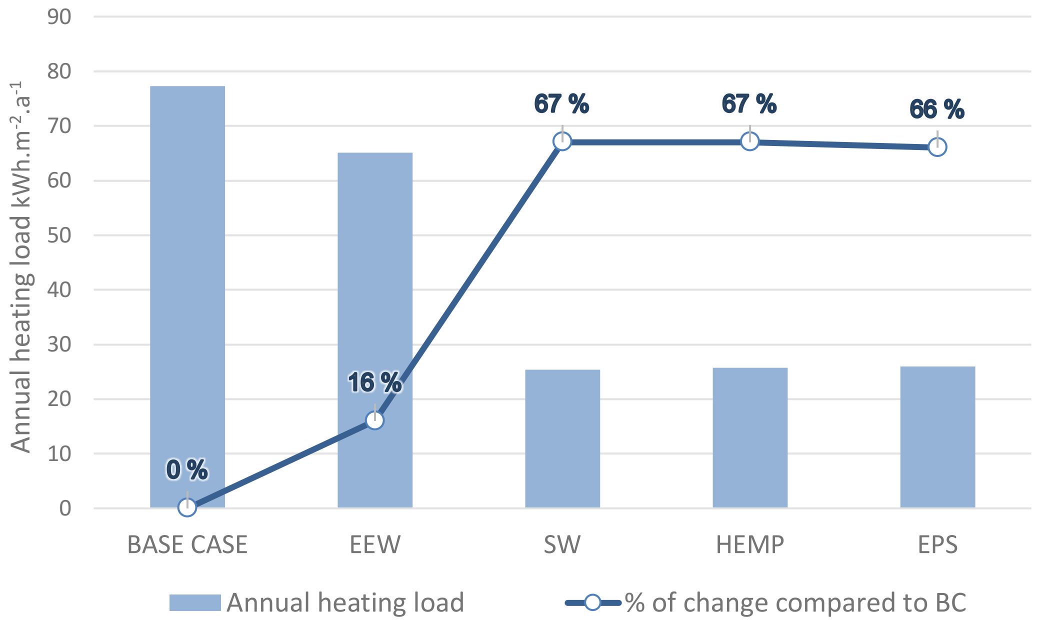


*Figure 48 Annual heating load of Kuyumdzieva house*

## 3.4 Internal gains

Internal gains are the heat gains (sensible and latent) inside a building derived from the number of occupants and their activity as well as electrical equipment and lights. Together with the solar gains they play a major role in the thermal comfort influencing the cooling demand, especially during the summer months. Figure 49 illustrates the internal gains for all examined buildings. They are the same for each building’s five cases because of the parameters stated in Table 6.

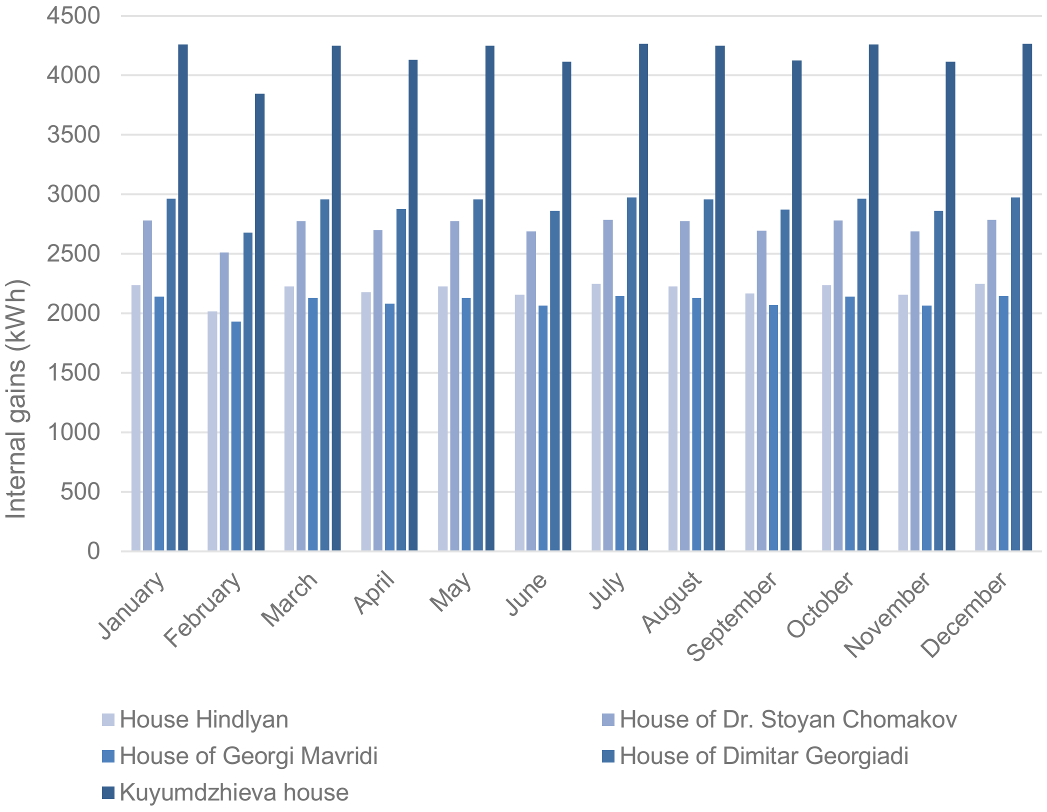


*Figure 49 Monthly internal gains in all of the five examined houses*

## 3.5 Solar gains

Solar gains are the heat earnings happening when solar short-wave radiation hits a building and warms it through the building envelope. They influence the thermal load and thus are key indicator for energy demand of a building. Figure 50 to Figure 54 visualize the monthly solar gains from each example building’s five cases.

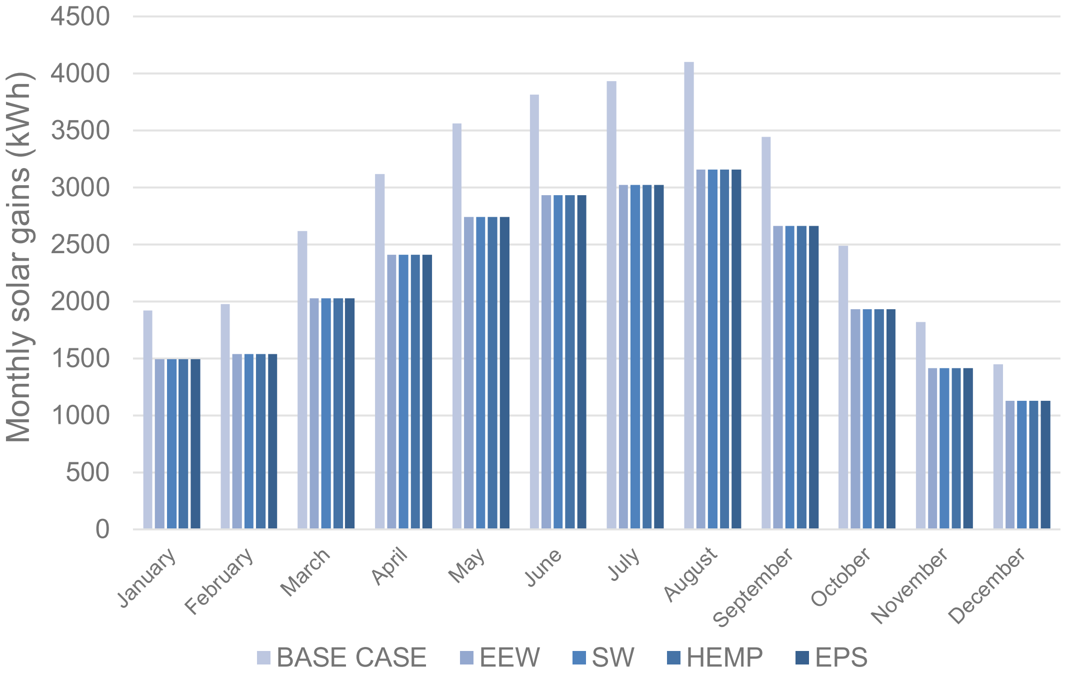


*Figure 50 Monthly solar gains of House Hindlyan*

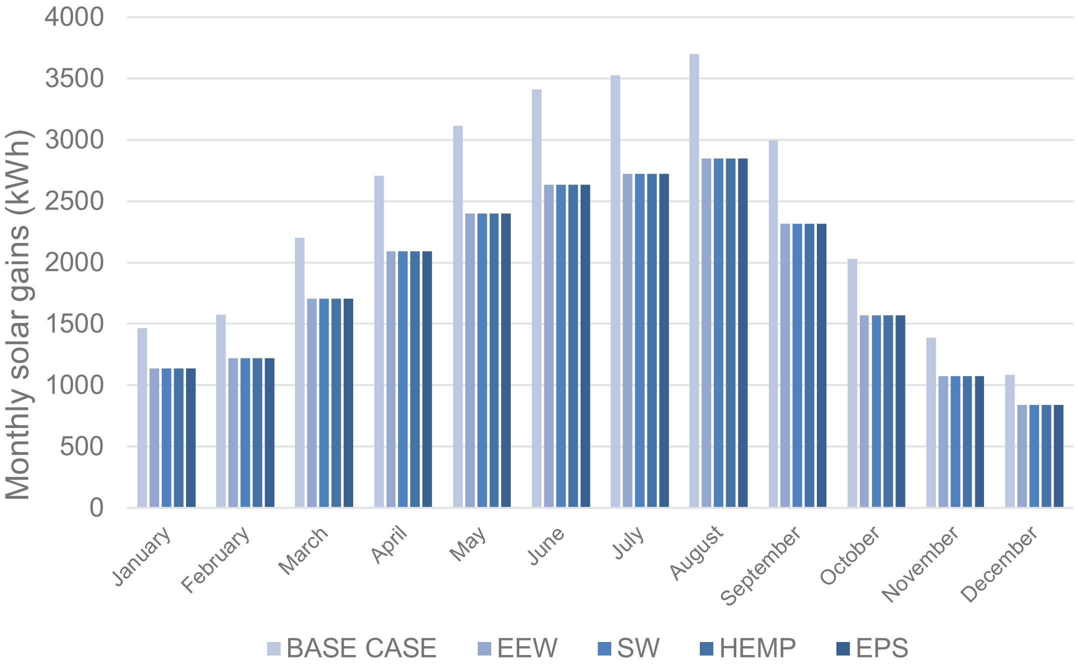


*Figure 51 Monthly solar gains of House of Dr. Stoyan Chomakov*

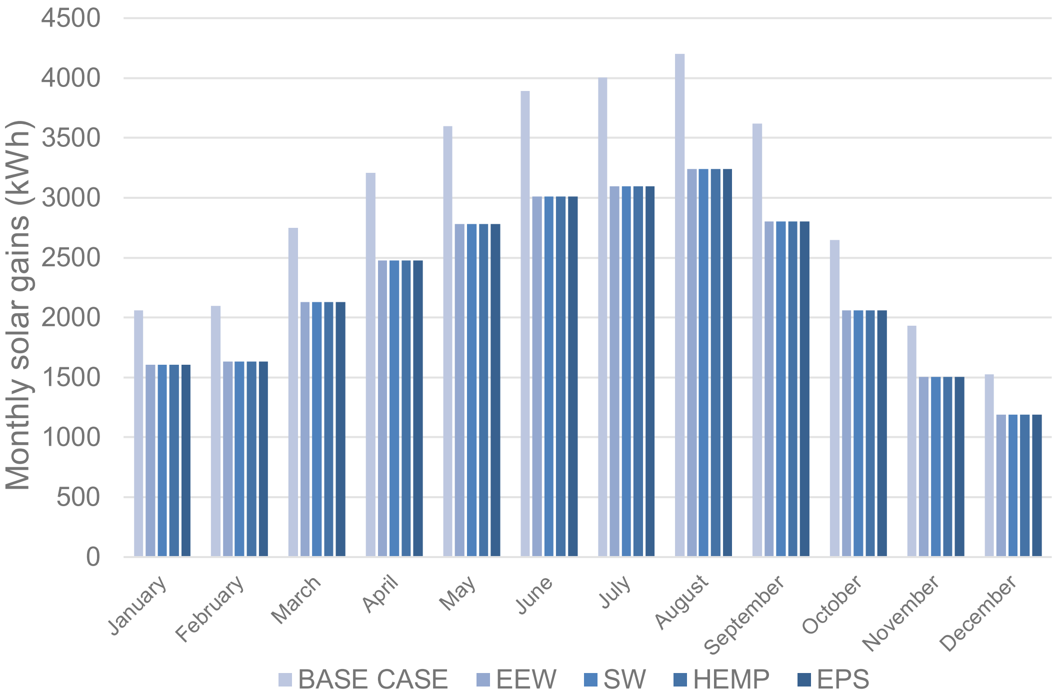


*Figure 52 Monthly solar gains of House of Georgi Mavridi (Lamartine House)*

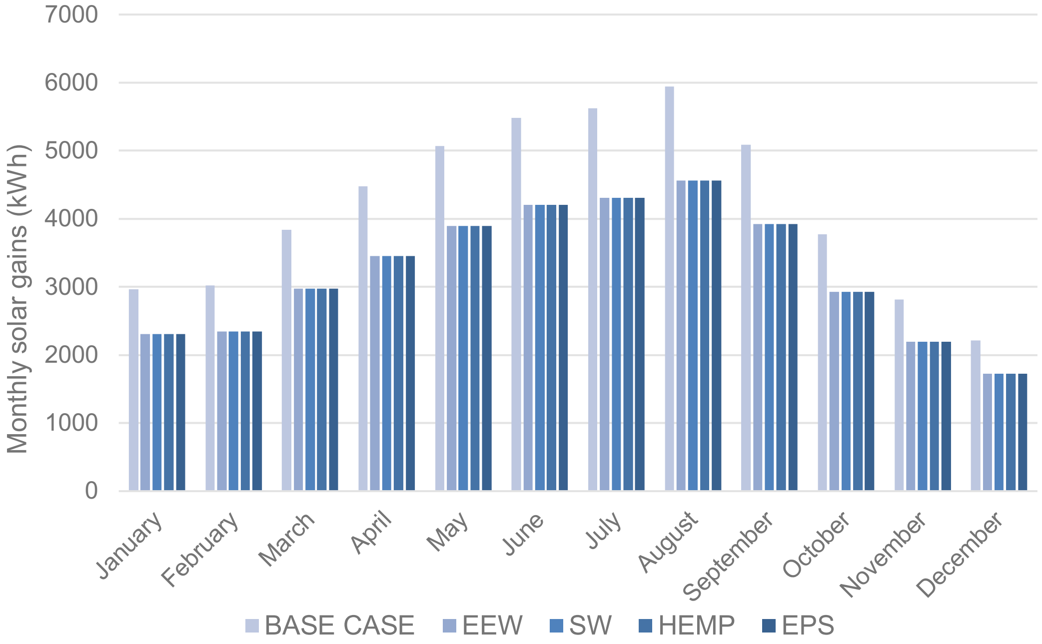


*Figure 53 Monthly solar gains of House of Dimitar Georgiadi*

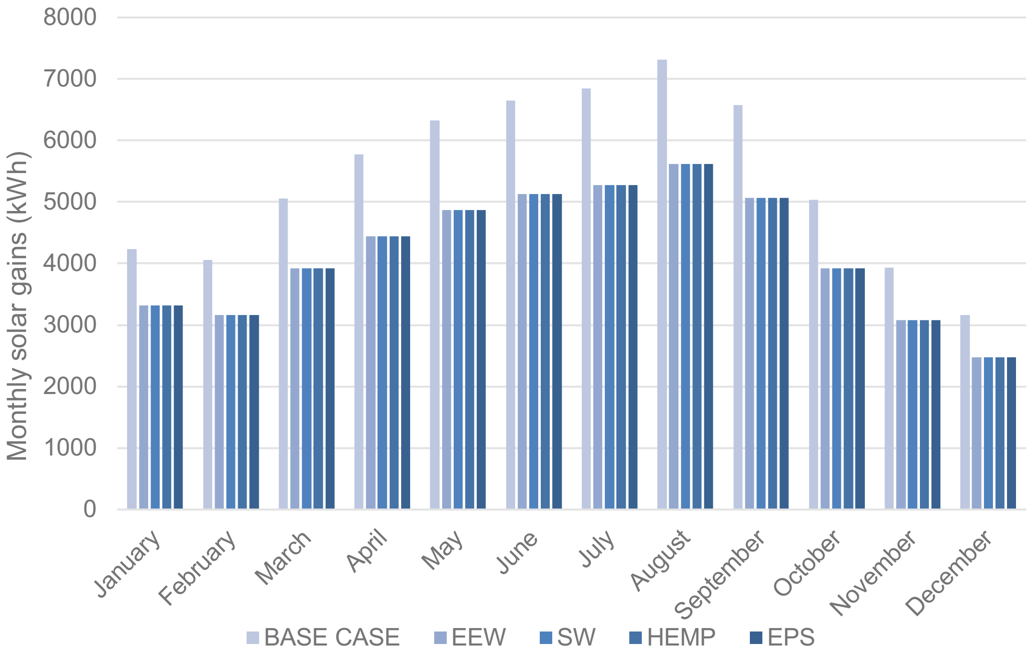


*Figure 54 Monthly solar gains of Kuyumdzieva house*

## 3.6 Transmission losses

The transmission of heat occurs through conduction, convection and radiation. Heat flows through the elements always in the direction of the lower temperature side (Second law of Thermodynamics). Transmission through the building construction elements happens via conduction every time when there is a temperature difference on both sides of the element. As visible in Equation 2 the U-value is a key element of the calculation of transmission heat losses and since it is influenced by the type and thickness of the layers of the building elements, they can be quite essential when striving to reduce the transmission losses of a building. Figure 55 to Figure 59 display the monthly transmission heat losses of each examined building.

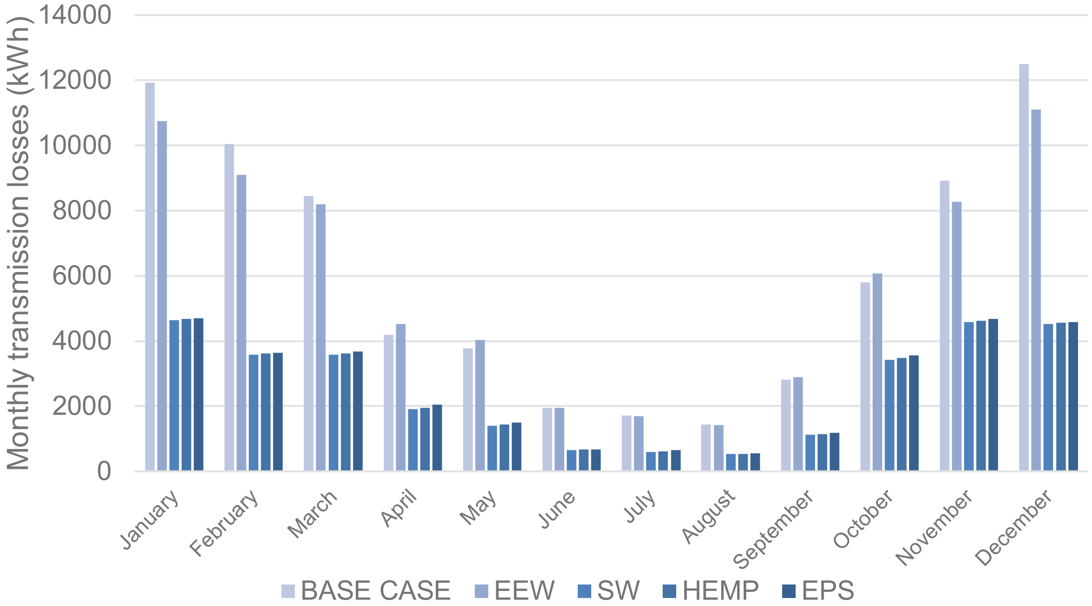


*Figure 55 Monthly transmission losses of House Hindlyan*

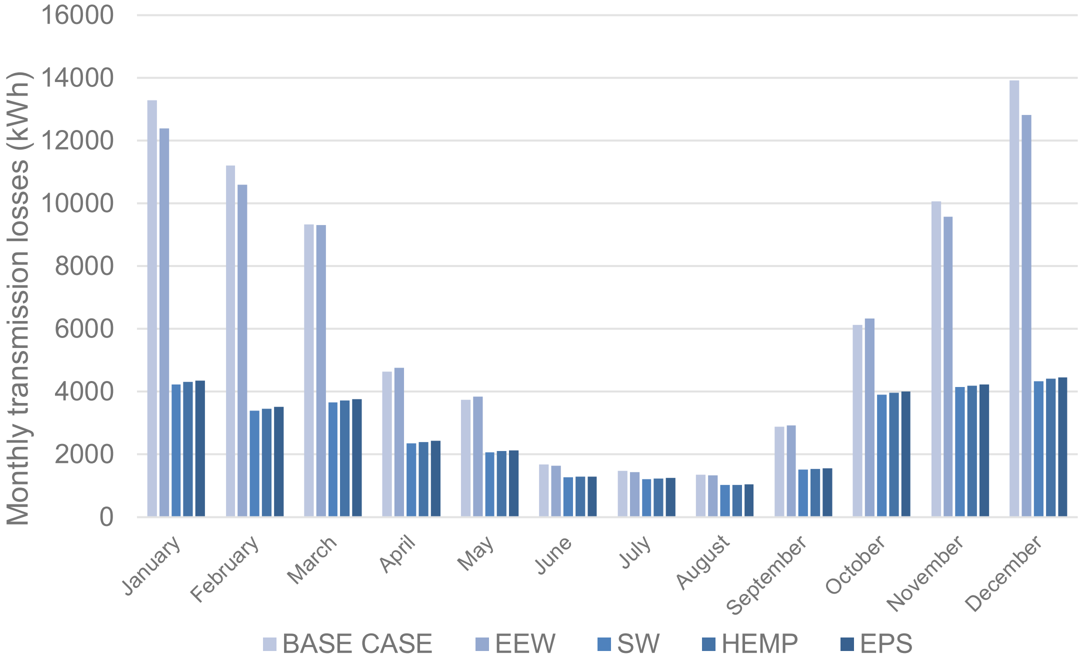


*Figure 56 Monthly transmission losses of House of Dr. Stoyan Chomakov*

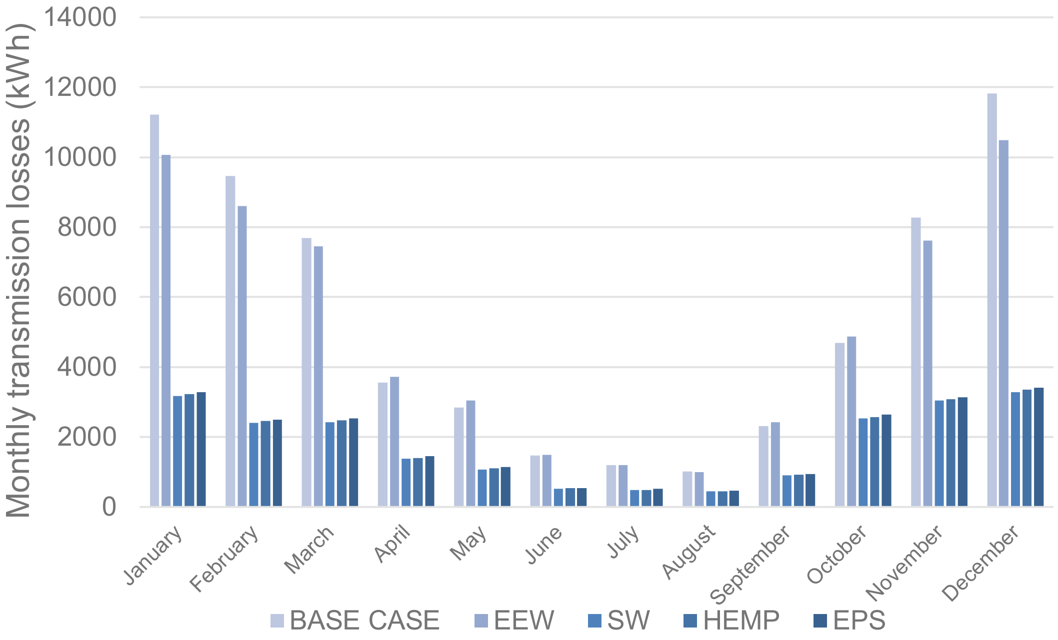


*Figure 57 Monthly transmission losses of House of Georgi Mavridi (Lamartine House)*

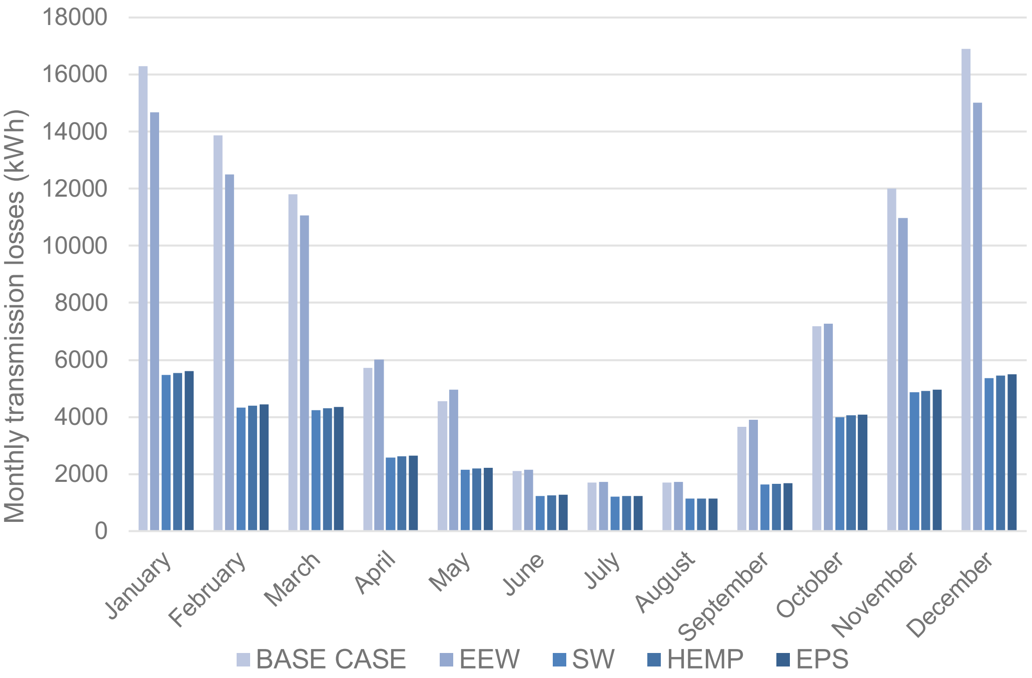


*Figure 58 Monthly transmission losses of House of Dimitar Georgiadi*

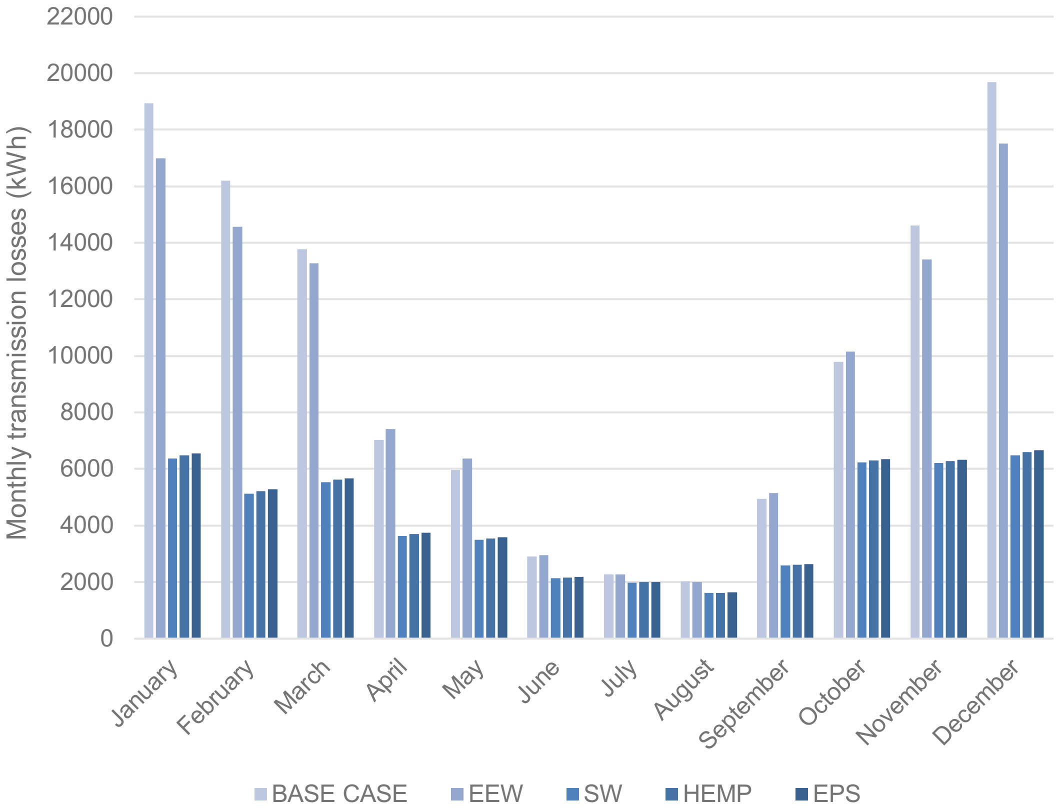


*Figure 59 Monthly transmission losses of Kuyumdzieva house*

## 3.7 Air change losses

Ventilation and infiltration are some of the primary causes of heat loss. The transfer of heated inside air to the outside surroundings and the return of colder air through the windows and doors (ventilation) and the building cracks (infiltration) plays a significant role in overall energy consumption. It is usually measured in ACH (air changes per hour) or in $m^3.s^{-1}.m^{-2}$ (infiltration rate per area façade). The simulation air change parameters are the same for all buildings as stated in the Bulgarian Regulation №7 (0.00035 $m^3.s^{-1}.m^{-2}$ for existing building stock – equal to approximately 0.6 ACH). Figure 60 to Figure 64 represent the air change losses of the evaluated houses.

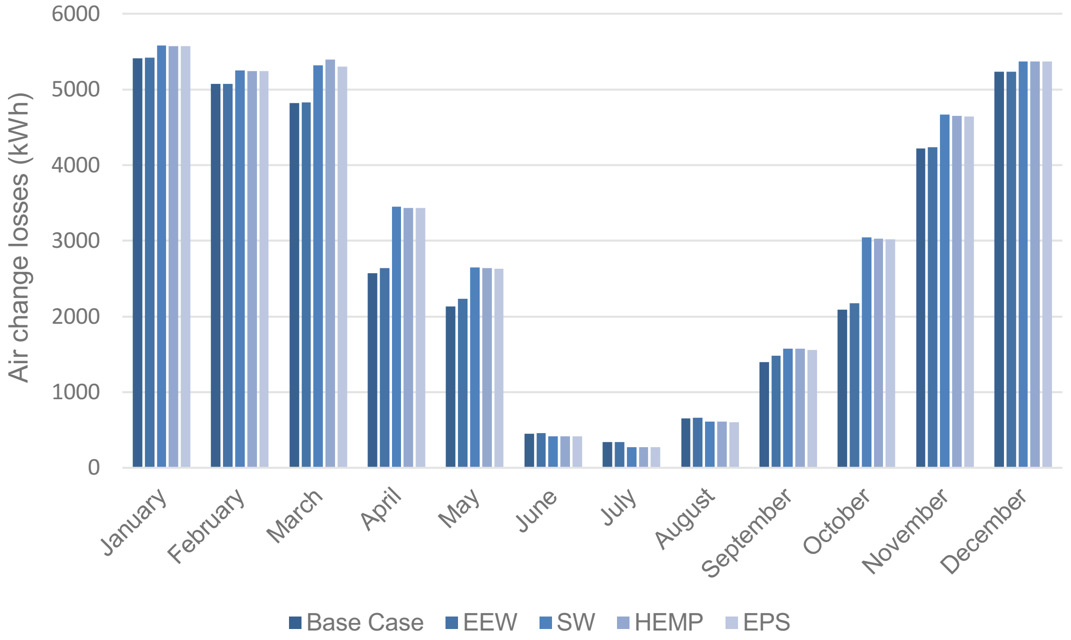


*Figure 60 Monthly air change losses of House Hindlyan*

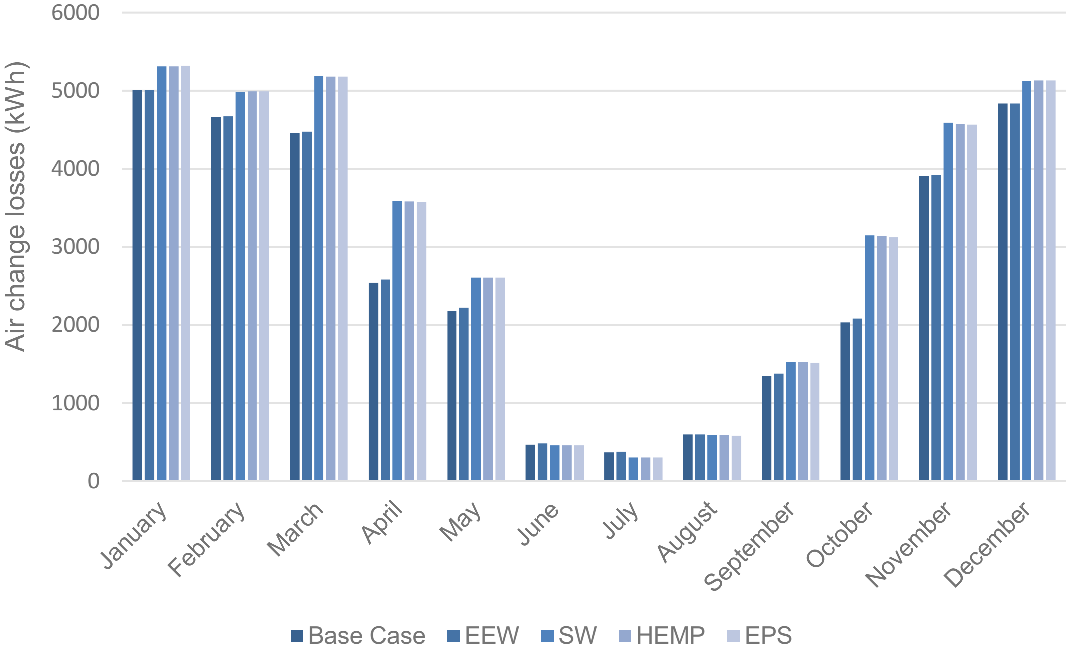


*Figure 61 Monthly air change losses of House of Dr. Stoyan Chomakov*

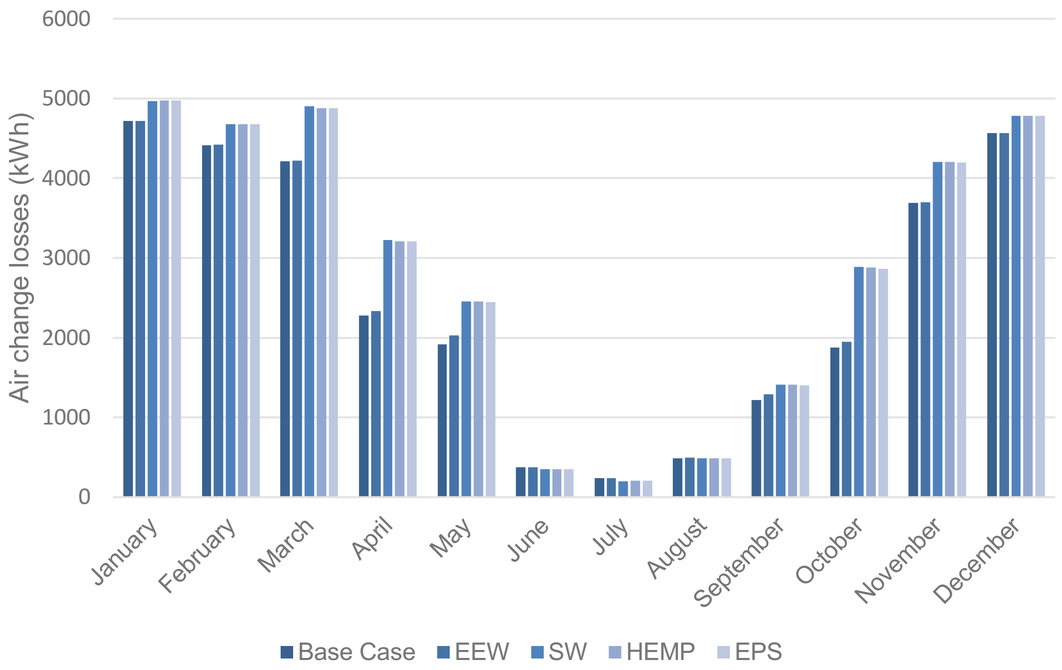


*Figure 62 Monthly air change losses of House of Georgi Mavridi (Lamartine House)*

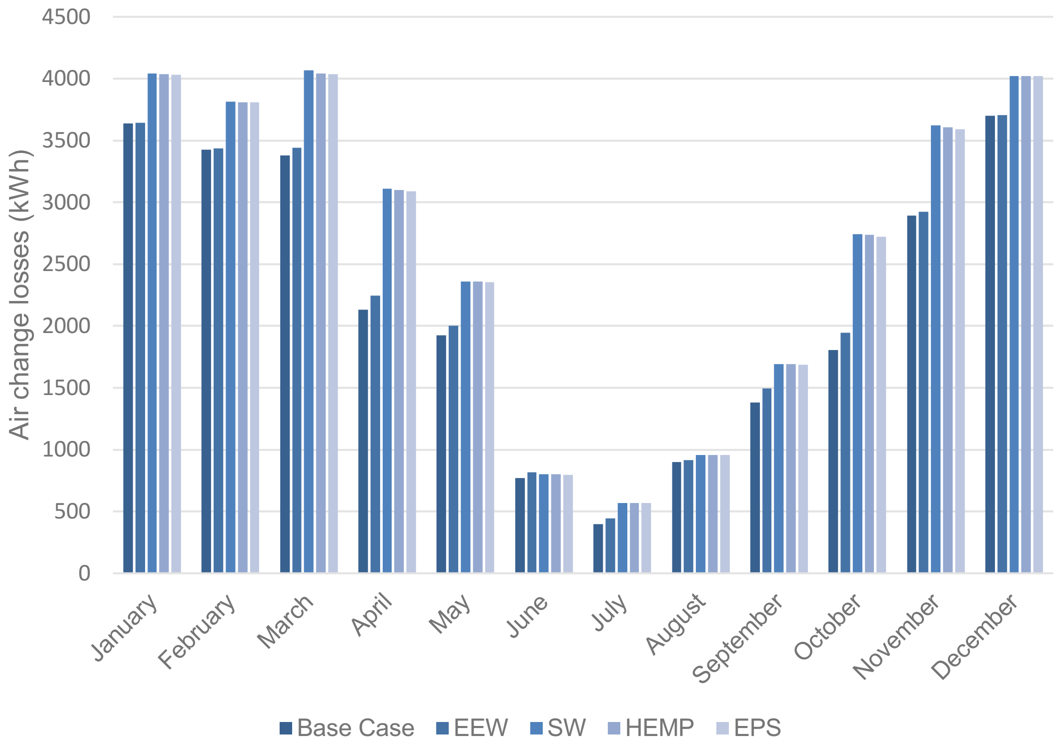


*Figure 63 Monthly air change losses of House of Dimitar Georgiadi*

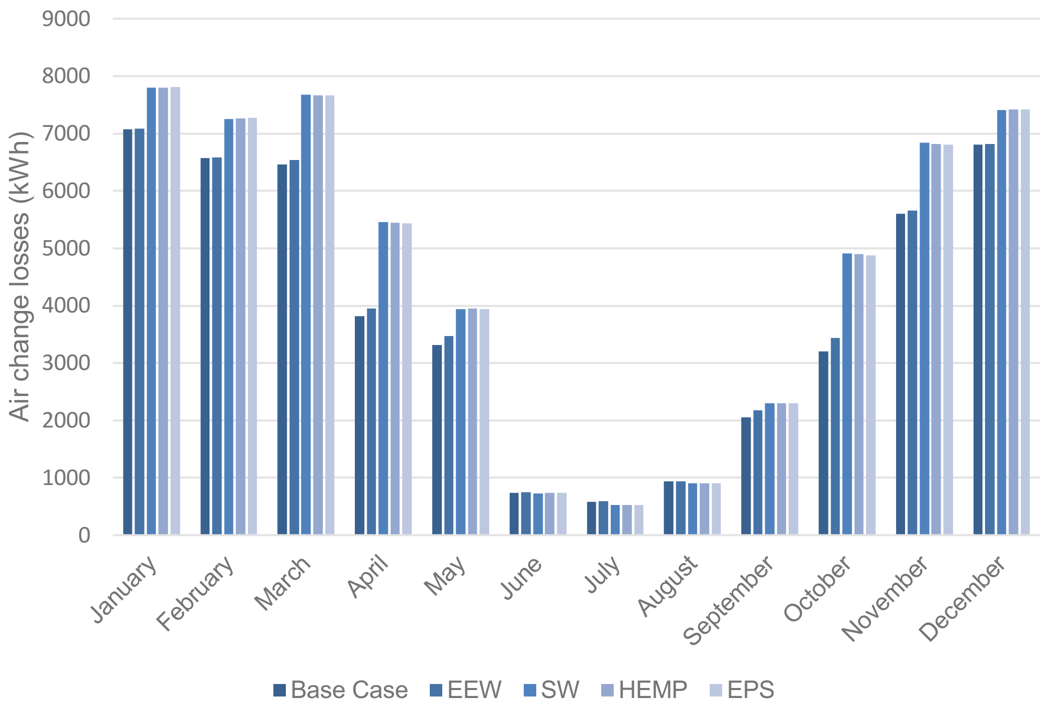


*Figure 64 Monthly air change losses of Kuyumdzieva house*

## 3.8 Summer overheating

Overheating historically has not been something that Europe struggled with, but with the rise of temperatures due to climate change (Global warming) it has become a problem of the present with the increase of overheating risk in the current building stock. Extreme temperatures are never comfortable and this is why energy-efficient design and refurbishment of old buildings are highly necessary. Europe has four different climatic zones and this is the reason there is no common building law regulating the comfortable temperatures . Bulgarian norms also do not have strict regulations when it comes to comfort temperatures. The calculation parameters stated in Table 4 suggest temperature levels for winter season but there is no detailed information on comfort temperatures specifically, especially for the summer season which is the problematic one in the climatic zone of Plovdiv. For the purposes of this research threshold temperature values are 18°C and 26°C. Outside of this range the indoor temperature is considered uncomfortable and requires heating or cooling. Also for the simulation, indoor temperature of 22°C is the threshold value above which ventilation is needed. Figure 65 to Figure 69 show the monthly cooling loads in each example house and its five cases. The necessity for cooling during the seasons is discussed in Chapter 4.9 with special attention to the temperature during the summer months.

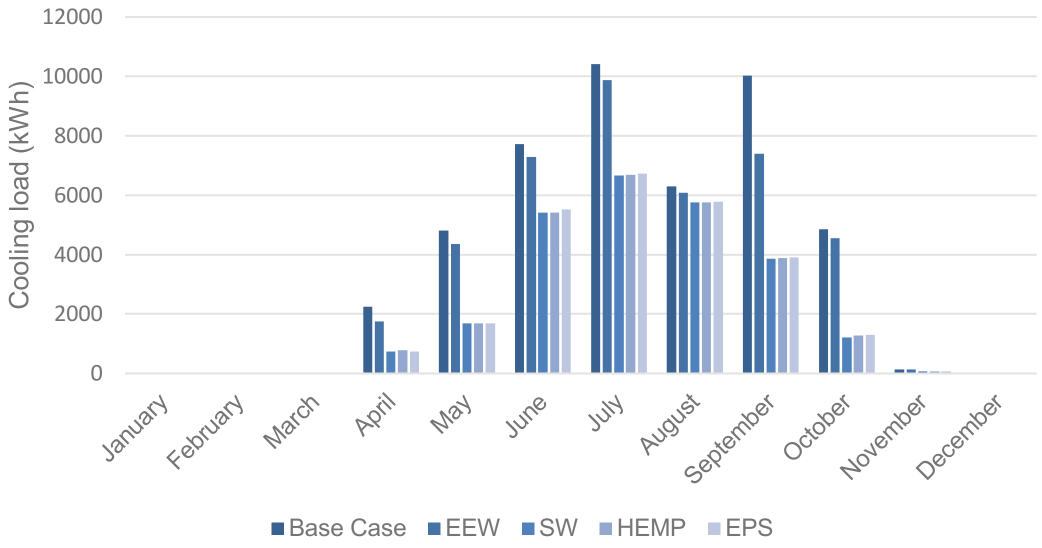


*Figure 65 Monthly cooling load of House Hindlyan*

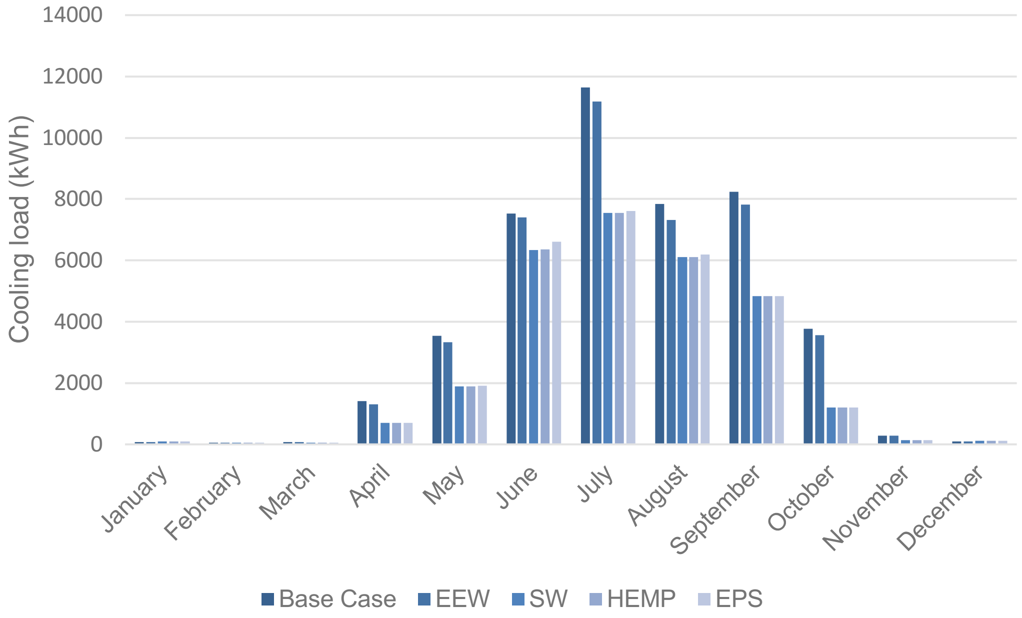


*Figure 66 Monthly cooling load of House of Dr. Stoyan Chomakov*

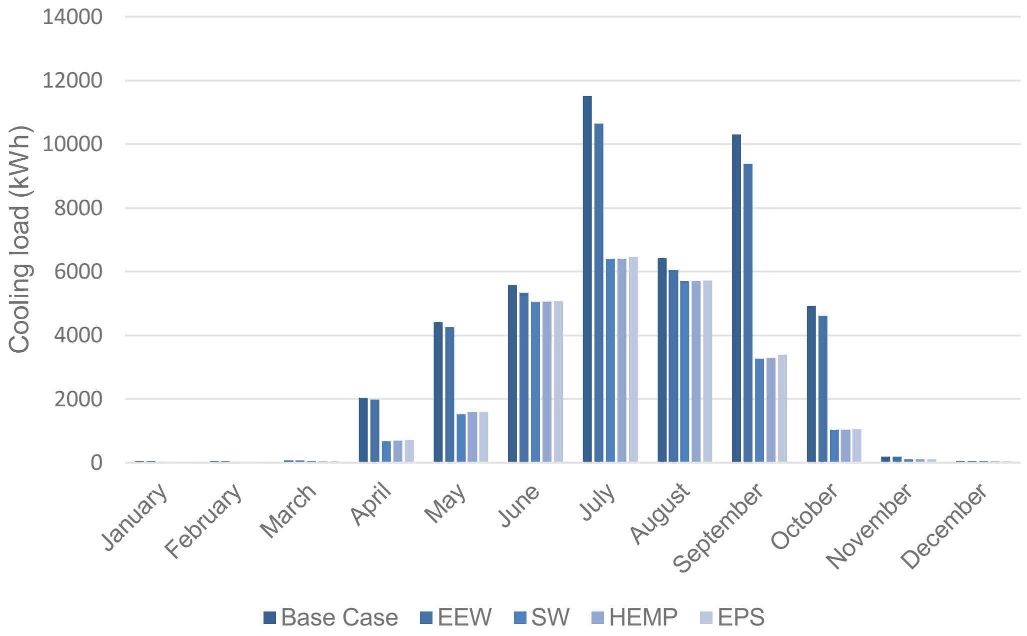


*Figure 67 Monthly cooling load of House of Georgi Mavridi (Lamartine House)*

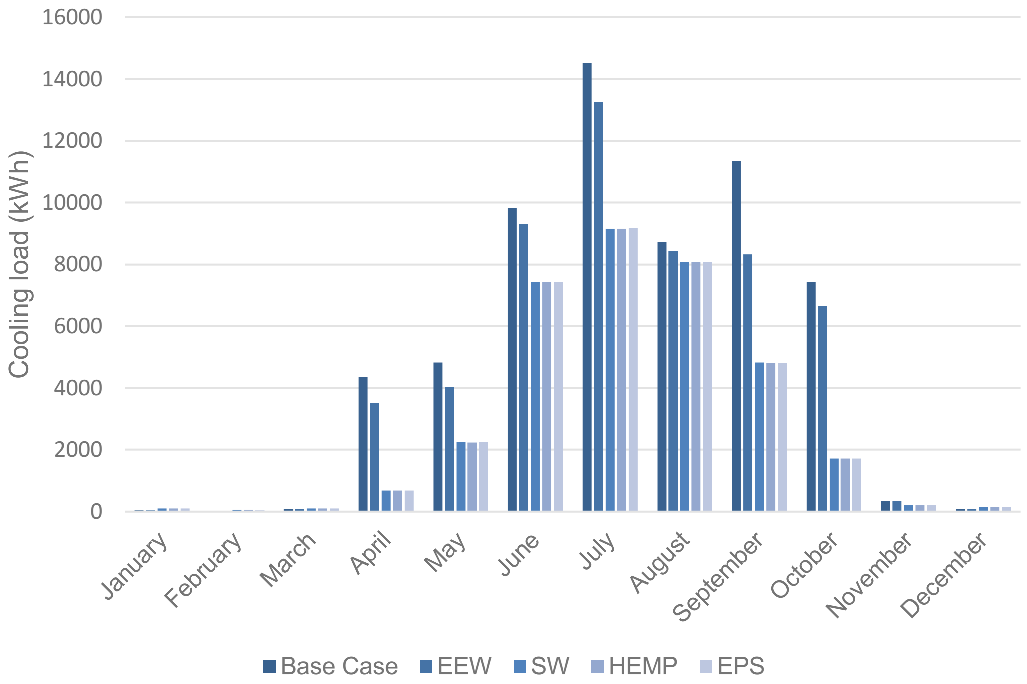


*Figure 68 Monthly cooling load of House of Dimitar Georgiadi*

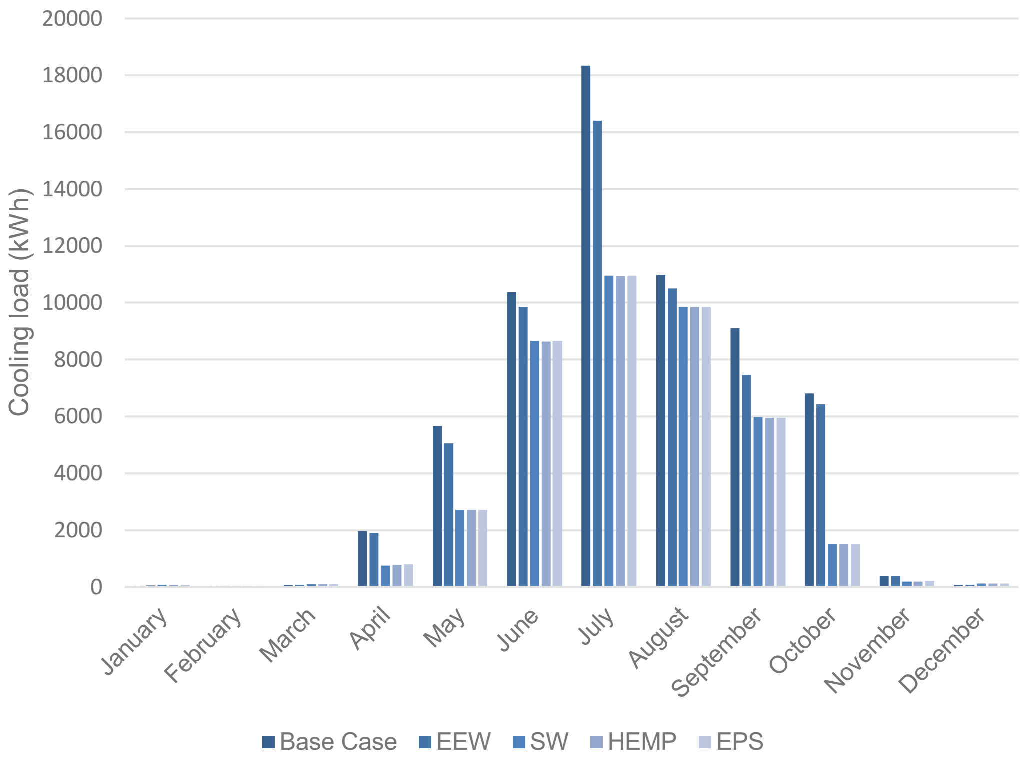


*Figure 69 Monthly cooling load of Kuyumdzieva house*

## 3.9 Daylight analysis

Daylight in buildings is a combination of different factors such as direct sunlight, diffuse skylight and sunlight that was reflected from the ground and the context surroundings. The evaluation of daylight is done using key parameters, namely illuminance levels and daylight factor. To analyze the daylight in the example buildings more than 100000 test points were created 75 cm above each building's floor surfaces. Results were gathered for each floor of a building separately and visualized later on. Figure 70 to Figure 74 illustrate the monthly average illuminance levels in each floor of the examined buildings with both windows – the base case with single pane windows and the optimized case with energy efficient windows.

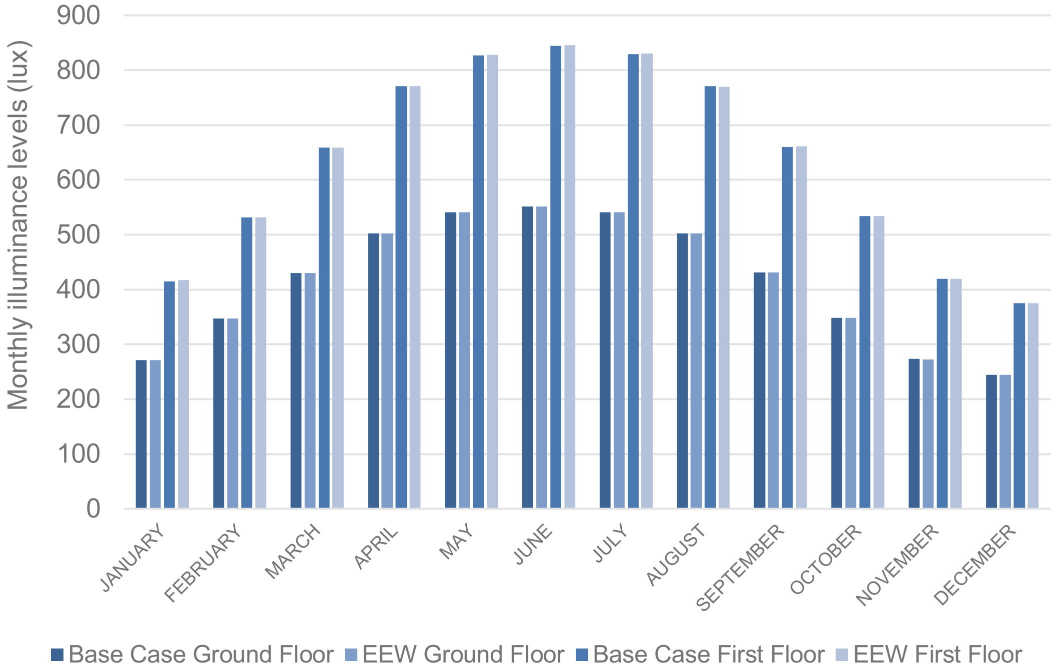


*Figure 70 Average illuminance levels of House Hindlyan taken for a specific representative date and time of the month*

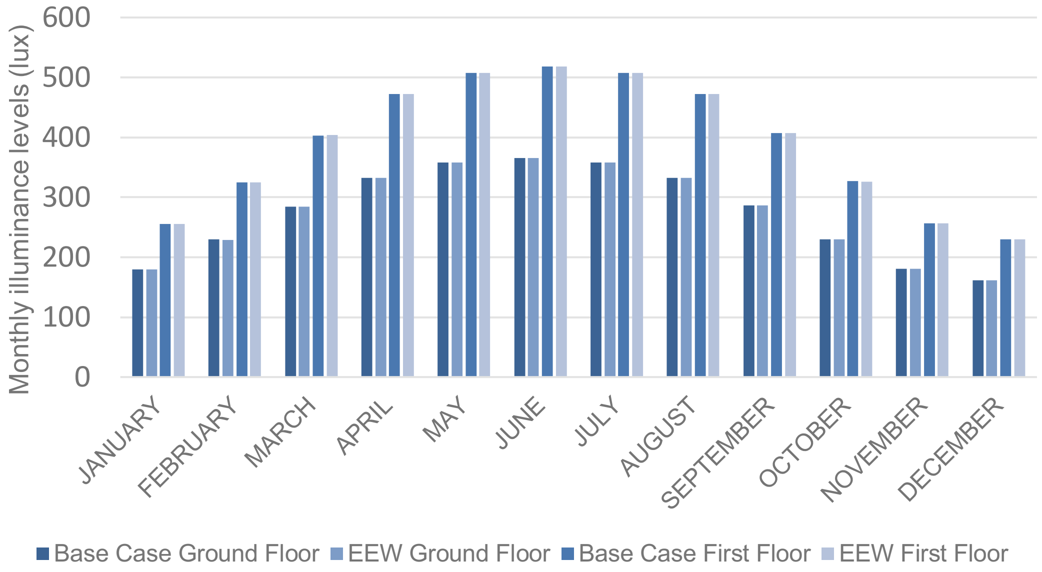


*Figure 71 Average illuminance levels of House Dr. Stoyan Chomakov taken for a specific representative date and time of the month*

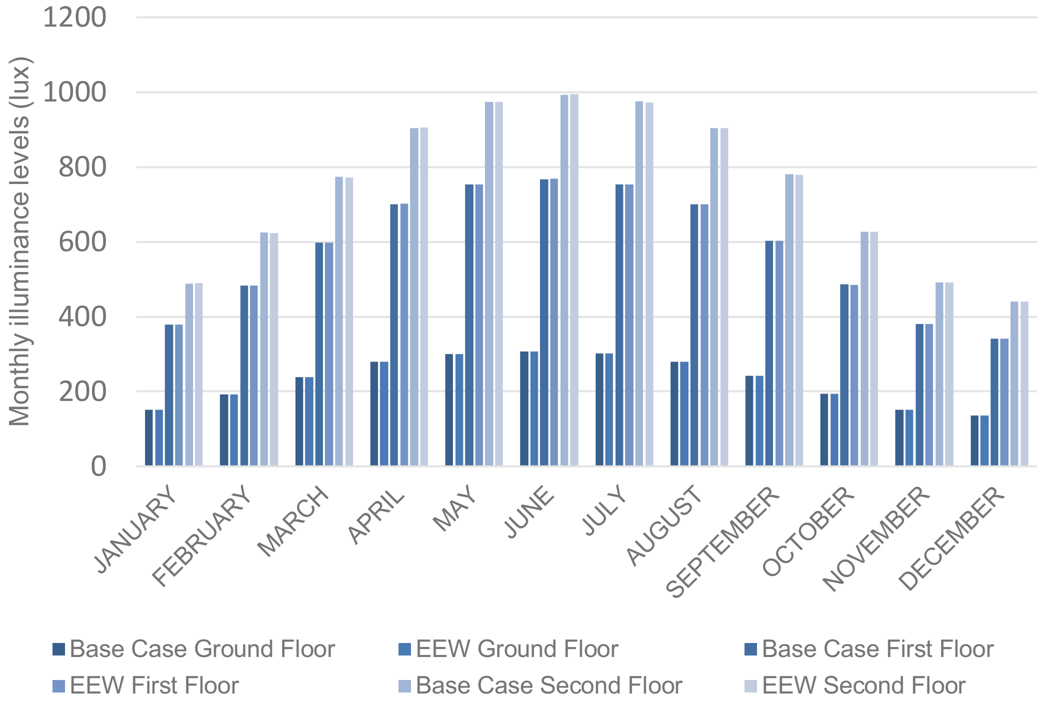


*Figure 72 Average illuminance levels of House Lamartine taken for a specific representative date and time of the month*

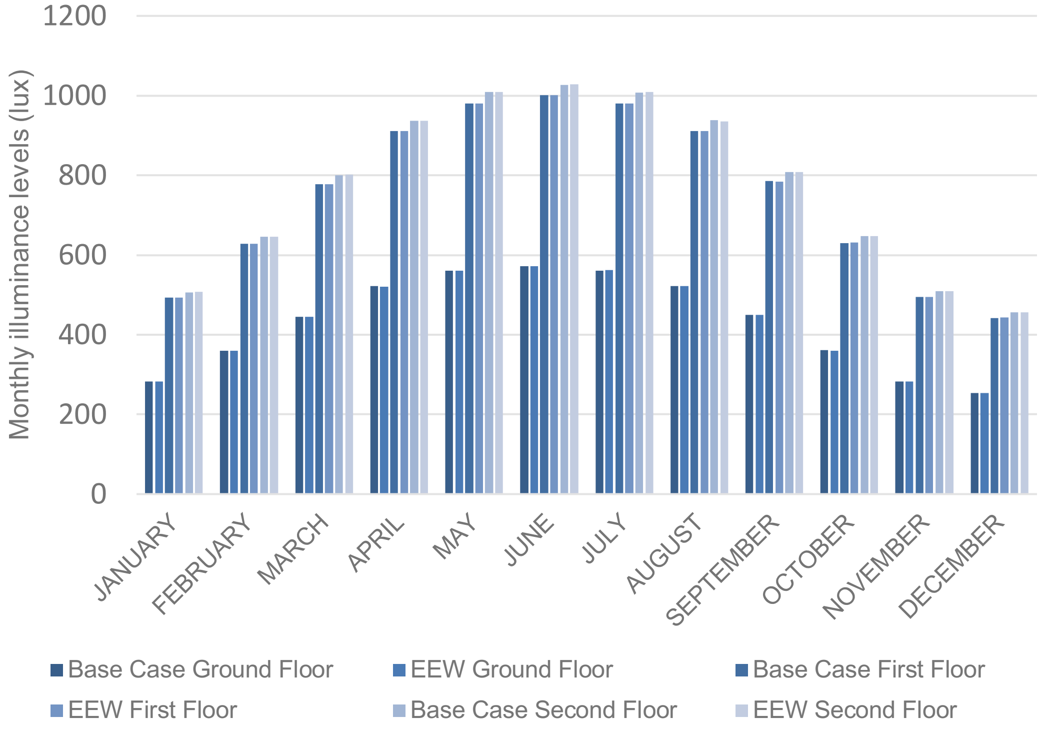


*Figure 73 Average illuminance levels of House Dimitar Georgiadi taken for a specific representative date and time of the month*

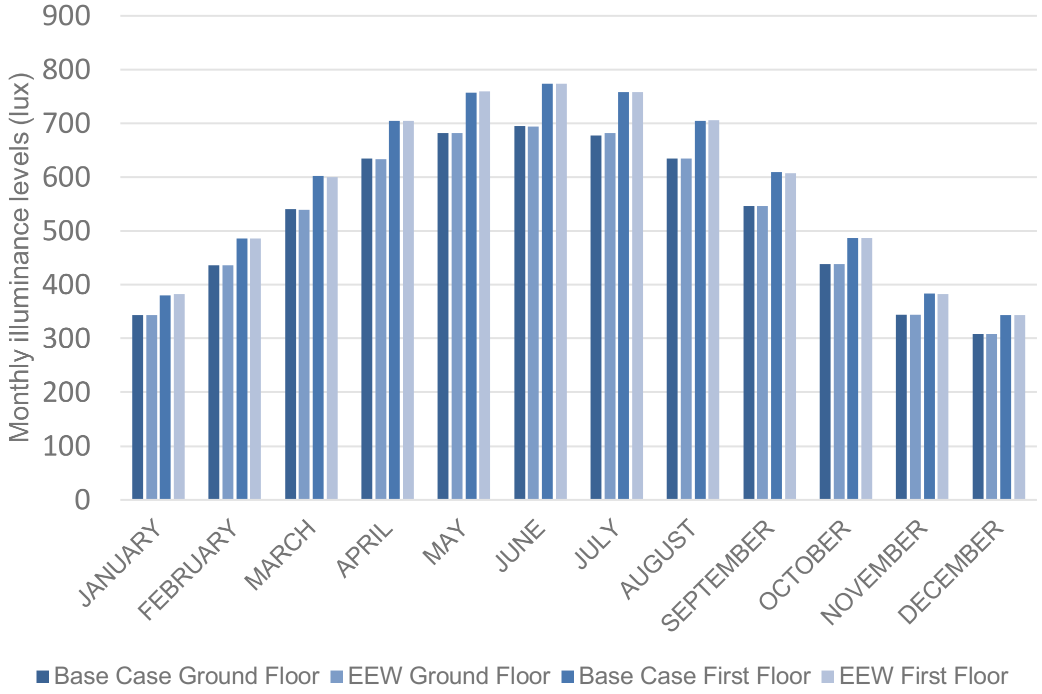


*Figure 74 Average illuminance levels of Kuyumdzieva house taken for a specific representative date and time of the month*

Special attention has been taken on the illuminance levels during the vernal (21th of March) and autumnal (22nd of September) equinoxes and the summer (21th of June) and winter (21th of December) solstices. The equinoxes are the only two times when there are almost equal amounts of daylight at all latitudes. During the summer solstice the sun is at its highest elevation and the winter solstice has the shortest day and longest night of the year.

Figure 75 and Figure 76 visualize the illuminance levels of each floor of House Hindlyan but the differences from both window cases are not distinct. Numeric results show more clearly the differences between the cases and the results can be seen in Table 11 and Table 12.

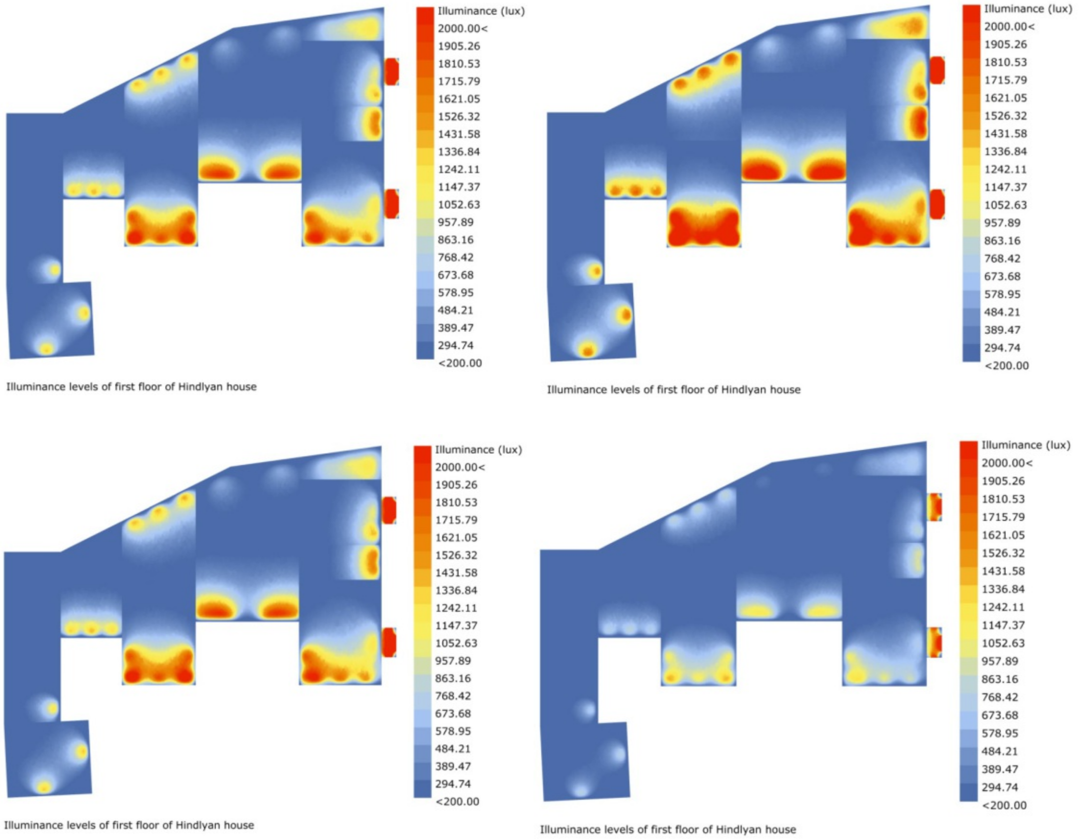


*Figure 75 Illuminance levels of Ground floor of House Hindlyan taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 11 Percentage of test points where the illuminance level is above 200 lux – House Hindlyan*

| | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ground floor BC | 41.07 | 48.69 | 57.13 | 64.28 | 68.02 | 68.67 | 67.86 | 64.58 | 57.21 | 48.90 | 41.26 | 38.03 |
| First floor BC | 63.09 | 70.51 | 75.55 | 79.78 | 81.47 | 83.56 | 83.15 | 79.74 | 75.41 | 70.68 | 63.48 | 59.59 |
| Ground floor EEW | 41.01 | 48.76 | 57.08 | 64.47 | 67.92 | 68.61 | 67.87 | 64.55 | 57.08 | 48.91 | 41.20 | 38.10 |
| First floor EEW | 63.31 | 70.33 | 75.56 | 79.61 | 83.05 | 83.81 | 83.18 | 79.67 | 75.48 | 70.58 | 63.49 | 59.60 |

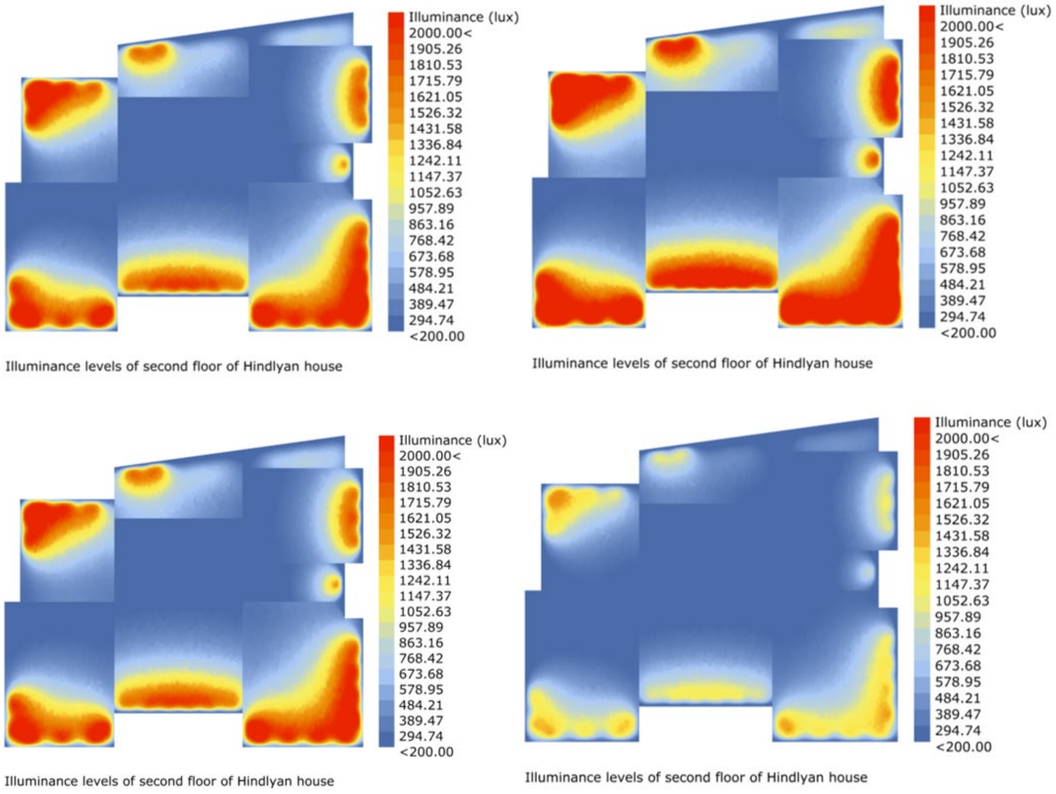


*Figure 76 Illuminance levels of First floor of House Hindlyan taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

The daylight factor is a measure of daylight availability calculating the amount of daylight that is available on a certain work plane compared to the amount of daylight available outside under overcast sky. The factor is expressed in percentage of available daylight and an average daylight factor was assessed for each building floor. The results of the assessment of all test points on the work plane were averaged and are shown in the following table:

*Table 12 Daylight factor – averages and % of test points with DF>2 – House Hindlyan*

| | Average Daylight Factor % | | % of test points with DF>2 | |
|---|---|---|---|---|
| | Ground Floor | First Floor | Ground Floor | First Floor |
| Basic windows case | 2.418 | 3.708 | 37.64 | 59.06 |
| Energy-efficient windows case | 2.416 | 3.713 | 37.62 | 59.03 |

Figure 77 and Figure 78 depict the illuminance levels of each floor of House of Dr. Stoyan Chomakov and Table 13 and Table 14 show the numeric results for percentage of test points with illuminance level above 200 lux and the daylight factors for each floor respectively.

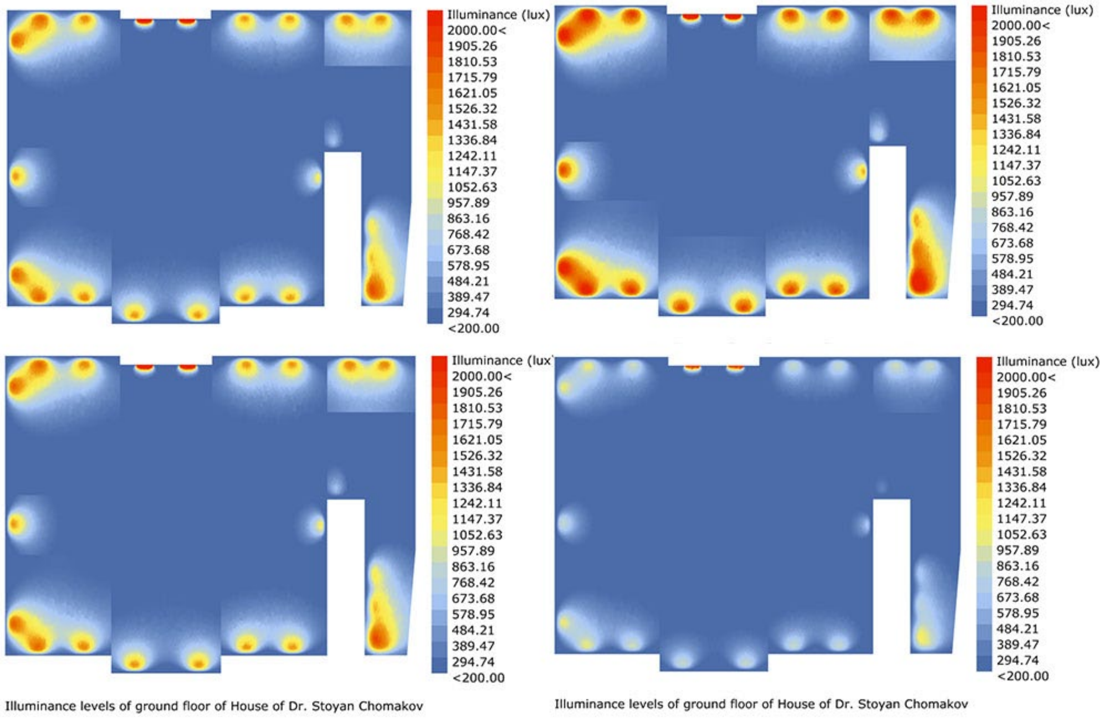


*Figure 77 Illuminance levels of Ground floor of House of Dr. Stoyan Chomakov taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 13 Percentage of test points where the illuminance level is above 200 lux – House of Dr. Stoyan Chomakov*

| | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ground floor BC | 30.90 | 37.60 | 44.27 | 49.52 | 51.34 | 51.78 | 51.31 | 49.46 | 44.87 | 37.80 | 31.08 | 28.20 |
| First floor BC | 41.26 | 50.39 | 60.06 | 66.41 | 68.92 | 70.23 | 69.09 | 66.36 | 60.47 | 50.65 | 41.30 | 37.54 |
| Ground floor EEW | 30.85 | 37.51 | 44.45 | 49.47 | 51.31 | 51.73 | 51.34 | 49.44 | 44.71 | 37.71 | 31.06 | 28.19 |
| First floor EEW | 41.34 | 50.51 | 60.11 | 66.25 | 69.09 | 69.97 | 69.34 | 66.19 | 60.42 | 50.60 | 41.50 | 37.55 |

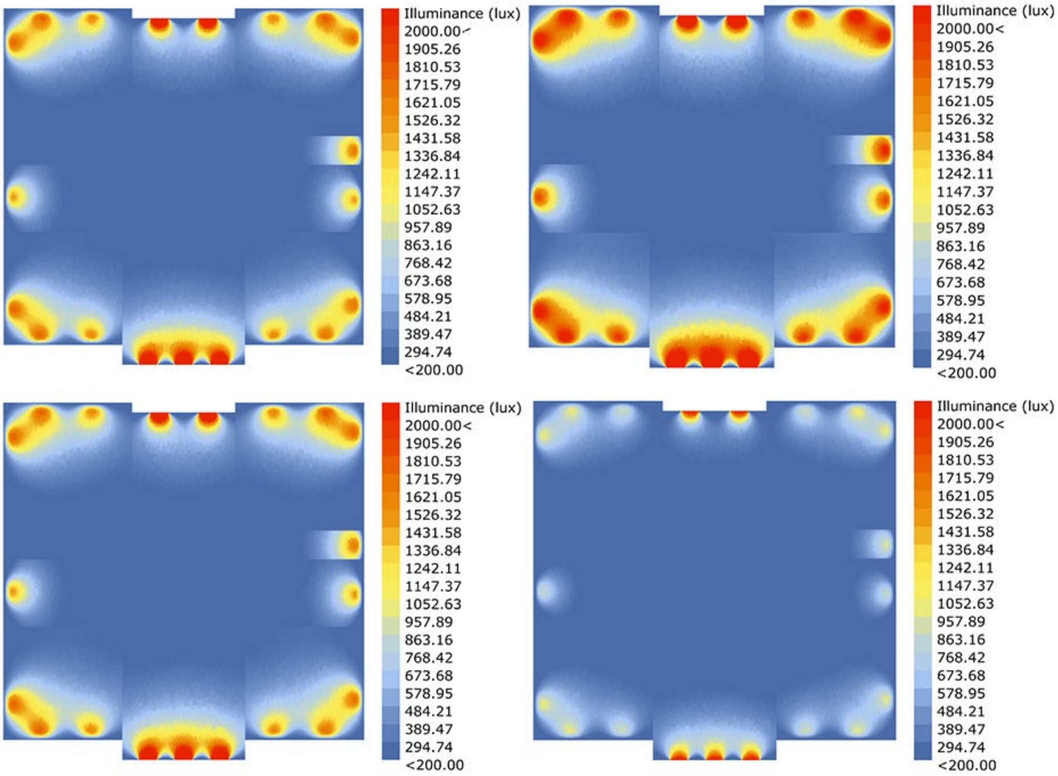
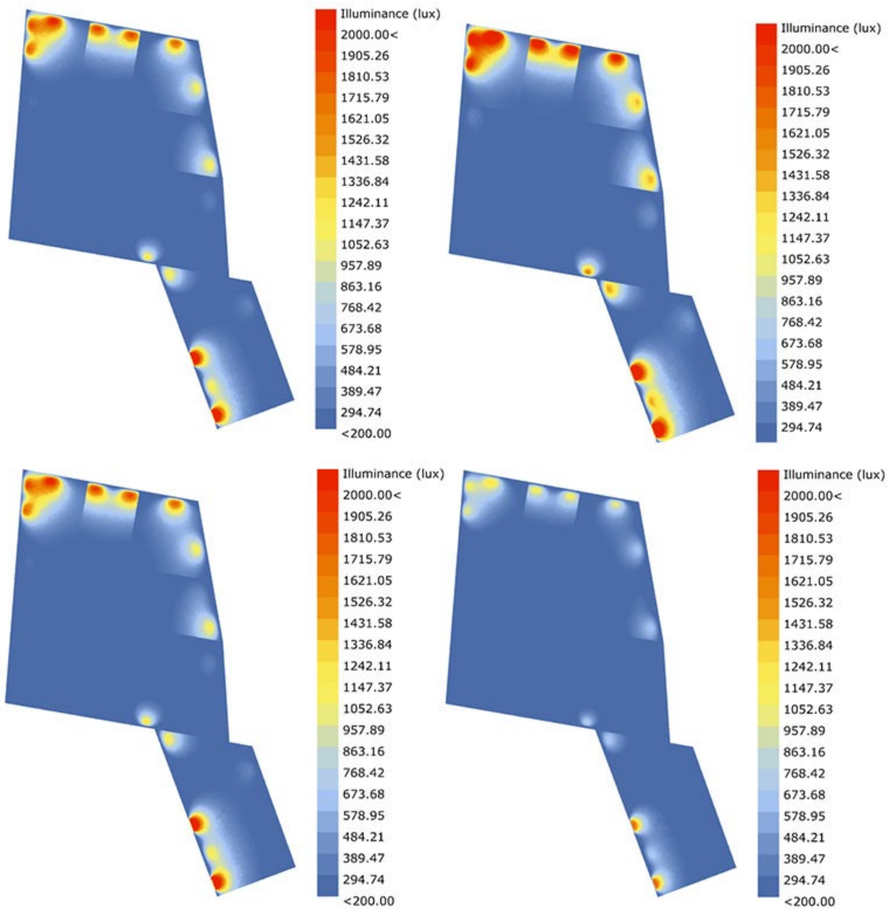


*Figure 78 Illuminance levels of First floor of House of Dr. Stoyan Chomakov taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 14 Daylight factor – averages and % of test points with DF>2 – House of Dr. Stoyan Chomakov*

| | Average Daylight Factor % | | % of test points with DF>2 | |
|---|---|---|---|---|
| | Ground Floor | First Floor | Ground Floor | First Floor |
| Basic windows case | 1.60 | 2.27 | 27.78 | 37.03 |
| Energy-efficient windows case | 1.59 | 2.27 | 27.83 | 37.04 |

Figure 79, Figure 80 and Figure 81 visualize the illuminance levels of each floor of House Lamartine and Table 15 and Table 16 show the numeric results for percentage of test points with illuminance level above 200 lux and the daylight factors for each floor respectively.



Illuminance levels of ground floor of Lamartine house

Illuminance levels of ground floor of Lamartine house

*Figure 79 Illuminance levels of Ground floor of House Lamartine taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 15 Percentage of test points where the illuminance level is above 200 lux – House Lamartine*

| | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ground floor BC | 22.38 | 28.27 | 35.38 | 41.14 | 44.19 | 45.37 | 44.37 | 41.18 | 35.74 | 28.43 | 22.52 | 20.02 |
| First floor BC | 59.85 | 65.87 | 70.54 | 74.05 | 76.25 | 76.80 | 76.35 | 74.09 | 70.83 | 65.91 | 59.97 | 56.86 |
| Second floor BC | 71.97 | 78.73 | 83.33 | 86.64 | 87.59 | 87.67 | 87.64 | 86.67 | 83.39 | 78.81 | 72.29 | 68.36 |
| Ground floor EEW | 22.37 | 28.27 | 35.37 | 41.18 | 44.39 | 45.31 | 44.34 | 41.19 | 35.62 | 28.35 | 22.44 | 20.01 |
| First floor EEW | 59.77 | 65.88 | 70.64 | 74.06 | 76.22 | 76.91 | 76.15 | 74.01 | 70.73 | 65.93 | 59.84 | 56.87 |
| Second floor EEW | 72.11 | 78.52 | 83.08 | 86.70 | 87.44 | 87.74 | 87.57 | 86.51 | 83.58 | 78.87 | 72.33 | 68.27 |

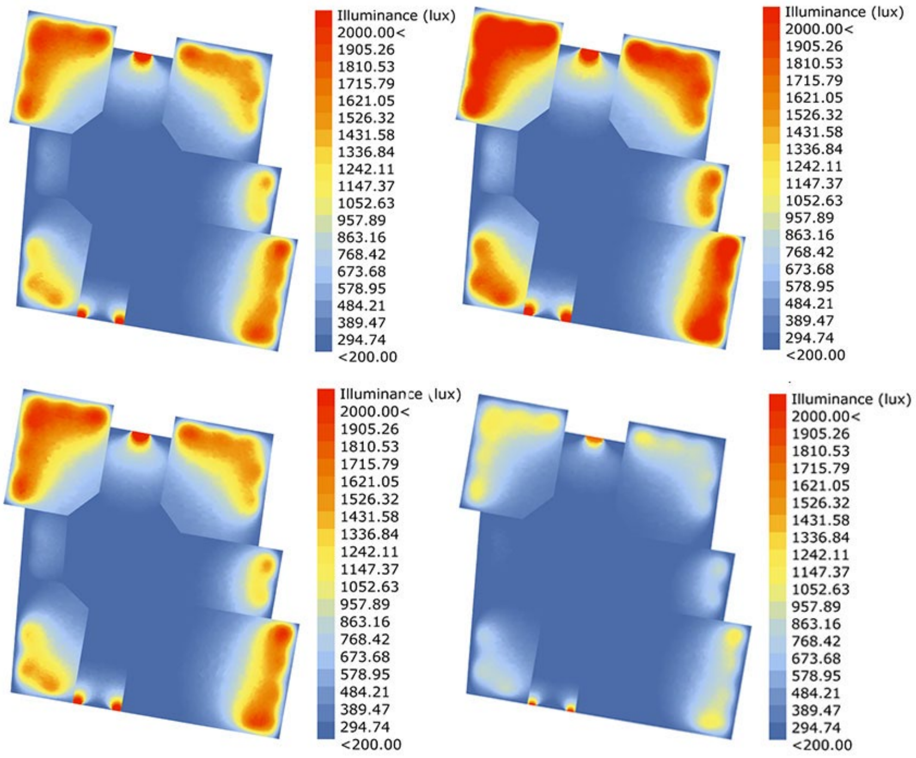


*Figure 80 Illuminance levels of First floor of House Lamartine taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 16 Daylight factor – averages and % of test points with DF>2 – House Lamartine*

| | Average Daylight Factor % | | | % of test points with DF>2 | | |
|---|---|---|---|---|---|---|
| | Ground Floor | First Floor | Second Floor | Ground Floor | First Floor | Second Floor |
| Basic windows case | 1.34 | 3.37 | 4.35 | 19.73 | 56.47 | 67.89 |
| Energy-efficient windows case | 1.35 | 3.37 | 4.36 | 19.71 | 56.47 | 67.84 |

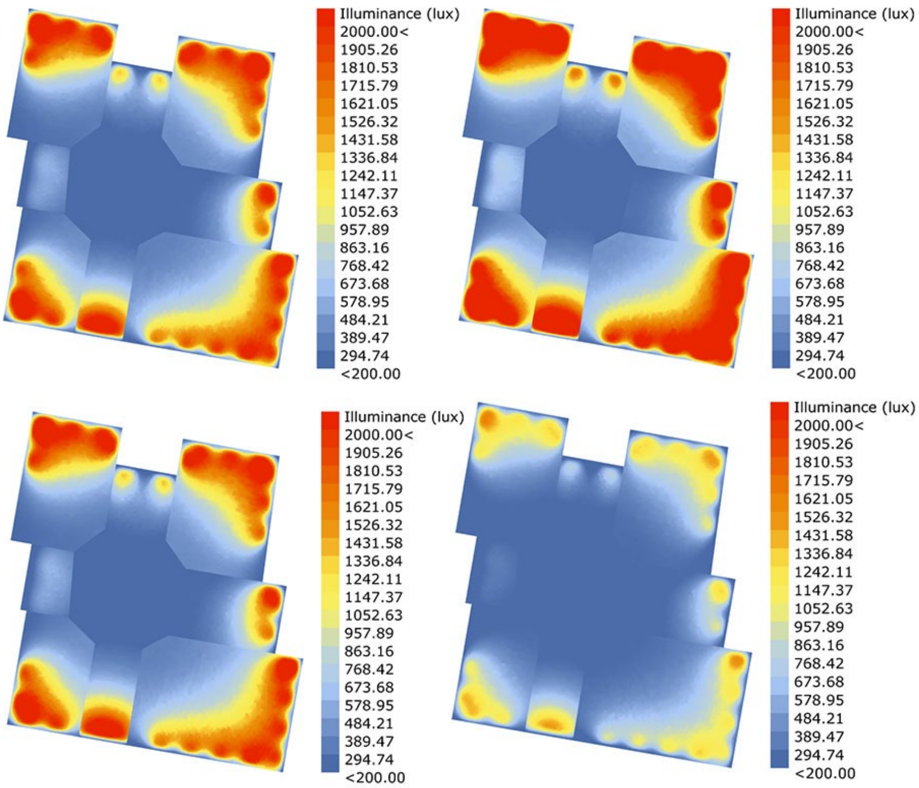


*Figure 81 Illuminance levels of Second floor of House Lamartine taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

Figure 82, Figure 83 and Figure 84 represent the illuminance levels of each floor of House of Dimitar Georgiadi and Table 17 and Table 18 give the numeric results for percentage of test points with illuminance level above 200 lux as well as the daylight factors for each floor.

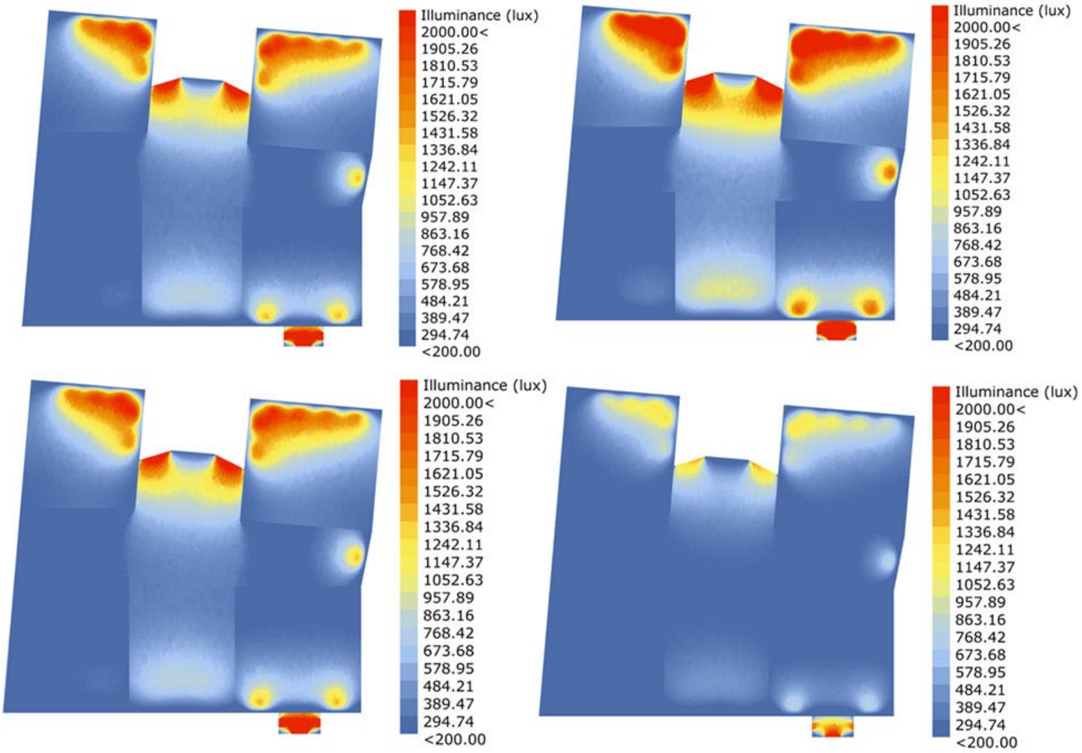


*Figure 82 Illuminance levels of Ground floor of House of Dimitar Georgiadi taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 17 Percentage of test points where the illuminance level is above 200 lux – House of Dimitar Georgiadi*

| | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ground floor BC | 50.14 | 61.20 | 68.13 | 71.82 | 73.84 | 74.81 | 74.01 | 71.82 | 68.13 | 61.45 | 50.67 | 43.87 |
| First floor BC | 73.73 | 81.21 | 90.66 | 93.28 | 93.70 | 93.79 | 93.67 | 93.33 | 91.15 | 81.29 | 73.93 | 68.48 |
| Second floor BC | 74.92 | 83.07 | 91.30 | 94.30 | 94.90 | 94.99 | 94.91 | 94.29 | 91.61 | 83.19 | 75.34 | 71.78 |
| Ground floor EEW | 50.13 | 61.33 | 67.98 | 71.90 | 74.09 | 74.65 | 74.30 | 71.91 | 68.22 | 61.34 | 50.37 | 43.70 |
| First floor EEW | 73.71 | 81.28 | 90.99 | 93.31 | 93.69 | 93.76 | 93.67 | 93.34 | 91.23 | 81.44 | 74.03 | 68.99 |
| Second floor EEW | 75.36 | 82.99 | 91.47 | 94.34 | 94.91 | 94.99 | 94.88 | 94.37 | 91.62 | 83.19 | 75.47 | 71.84 |

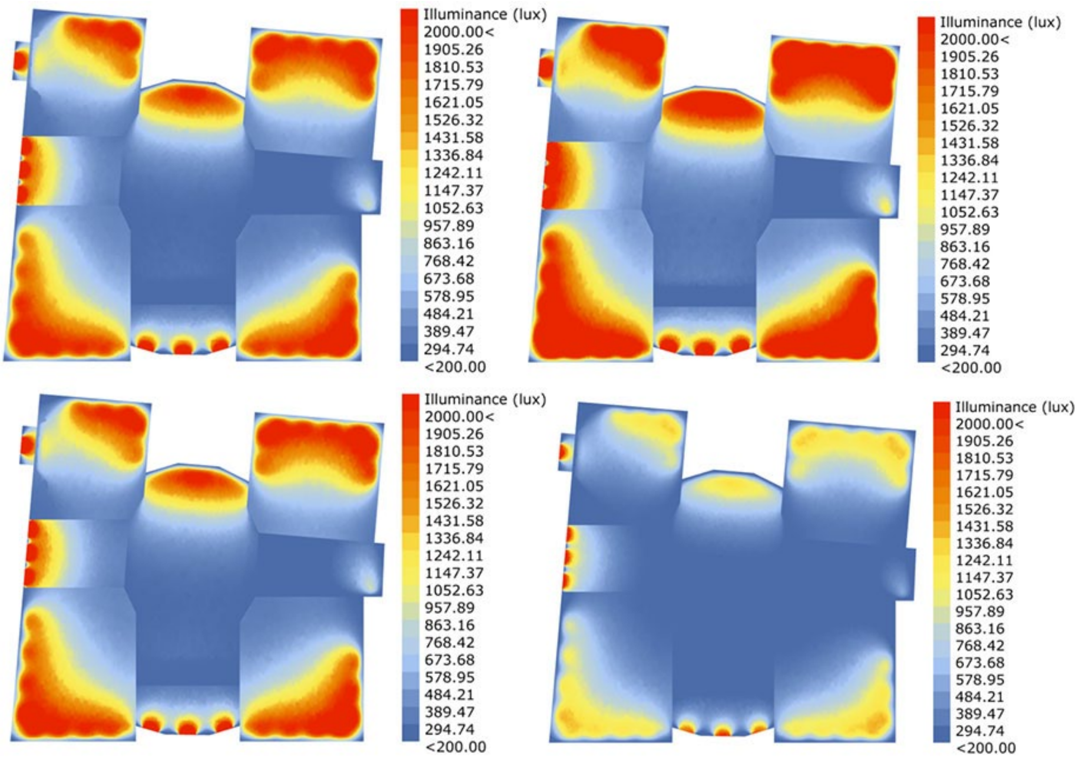


*Figure 83 Illuminance levels of First floor of House of Dimitar Georgiadi taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 18 Daylight factor – averages and % of test points with DF>2 – House of Dimitar Georgiadi*

| | Average Daylight Factor % | | | % of test points with DF>2 | | |
|---|---|---|---|---|---|---|
| | Ground Floor | First Floor | Second Floor | Ground Floor | First Floor | Second Floor |
| Basic windows case | 2.51 | 4.37 | 4.51 | 43.20 | 67.79 | 71.34 |
| Energy-efficient windows case | 2.51 | 4.39 | 4.51 | 43.21 | 68.32 | 71.29 |

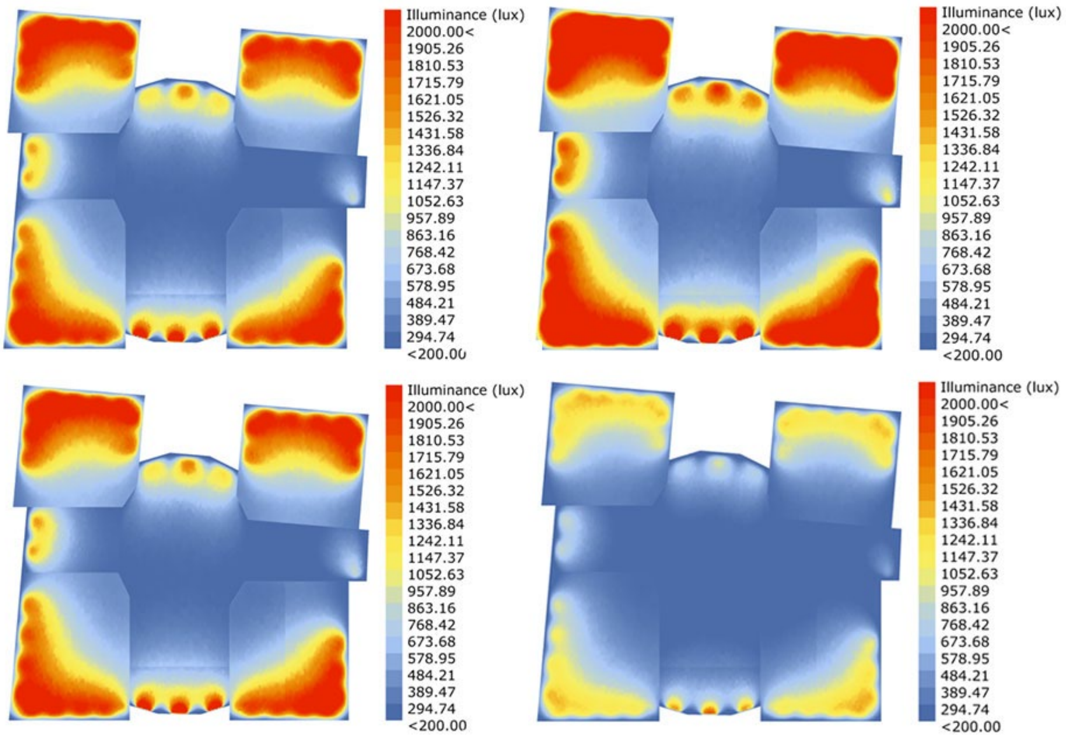


*Figure 84 Illuminance levels of Second floor of House of Dimitar Georgiadi taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

The illuminance levels of each floor of Kuyumdzieva house can be seen in Figure 85 and Figure 86, the numeric results for percentage of test points with illuminance level above 200 lux are shown in Table 19 as well as the daylight factors for each floor which are given in Table 20 .

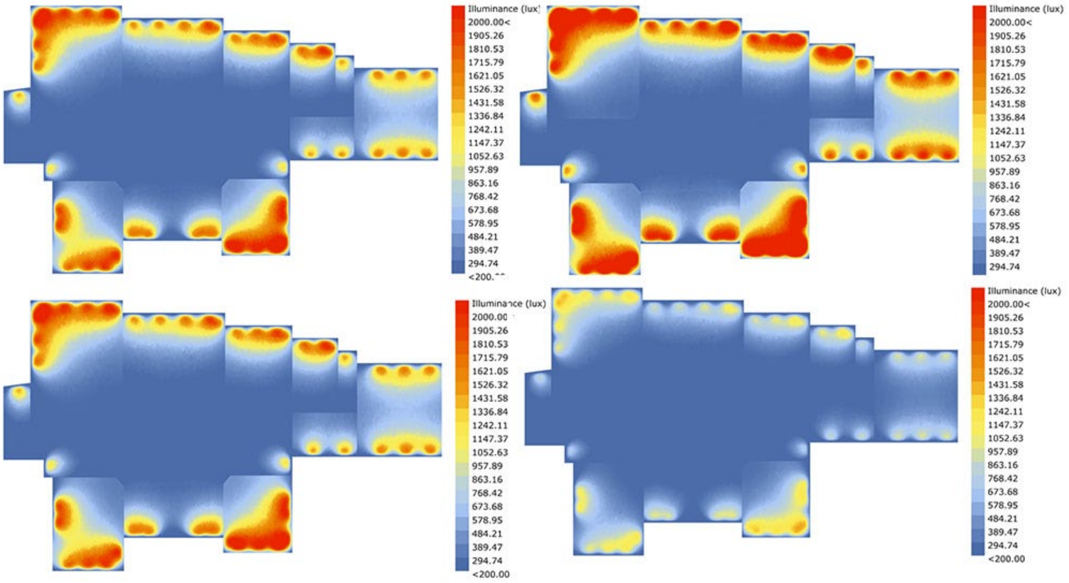


*Figure 85 Illuminance levels of Ground floor of Kuyumdzieva house taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 19 Percentage of test points where the illuminance level is above 200 lux – Kuyumdzieva house*

| | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ground floor BC | 55.14 | 61.29 | 67.27 | 72.61 | 75.06 | 75.28 | 74.49 | 73.03 | 67.67 | 61.45 | 55.13 | 51.94 |
| First floor BC | 57.64 | 63.04 | 67.83 | 71.73 | 73.39 | 74.64 | 73.56 | 71.64 | 68.27 | 62.95 | 57.86 | 54.67 |
| Ground floor EEW | 55.07 | 61.28 | 67.52 | 72.62 | 75.26 | 75.10 | 74.94 | 72.77 | 67.90 | 61.51 | 55.29 | 52.01 |
| First floor EEW | 57.83 | 62.99 | 67.43 | 71.72 | 74.05 | 74.56 | 73.89 | 71.79 | 68.20 | 63.03 | 57.72 | 54.68 |

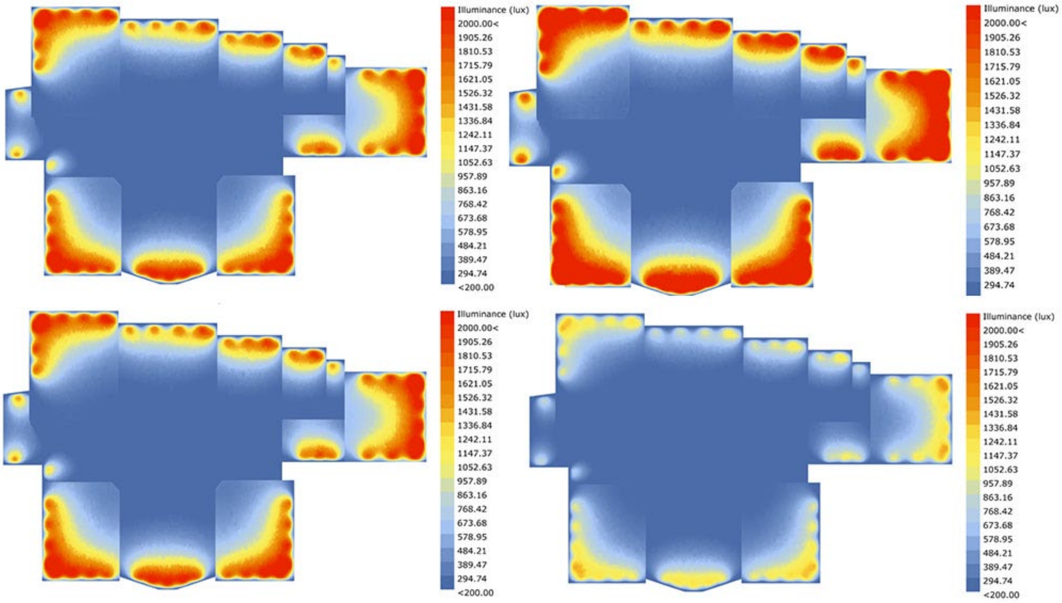


*Figure 86 Illuminance levels of First floor of Kuyumdzieva house taken for the annual equinoxes and solstices UP left – vernal equinox (21th of March), UP right - summer solstice (21th of June), DOWN left - autumnal equinox (22nd of September), DOWN right – winter solstice (21th of December)*

*Table 20 Daylight factor – averages and % of test points with DF>2 – Kuyumdzieva house*

| | Average Daylight Factor % | | % of test points with DF>2 | |
|---|---|---|---|---|
| | Ground Floor | First Floor | Ground Floor | First Floor |
| Basic windows case | 3.05 | 3.39 | 51.58 | 54.30 |
| Energy-efficient windows case | 3.05 | 3.40 | 51.60 | 54.27 |

# 4 DISCUSSION

The main focus of this chapter is the interpretation of the results obtained in the parametric study. All graphs illustrating those results are shown in the previous chapter. The discussion is separated in sections titled with each evaluated parameter (temperature, relative humidity, energy demand, transmission losses, air change losses, solar gains, internal gains) as well as summer overheating risk and daylight.

## 4.1 Temperature

Temperature is a key parameter for thermal analysis and is often the first thing which comes to mind when describing thermal comfort. Chapter 3.1 contains the simulation results visualized with graphs. The simulated temperature results were averaged for each month of each evaluated house and are shown in Figure 29 to Figure 33. Those graphs show very similar temperature levels in each house which is most probably resulted by the same indoor conditions used for the simulation (2.10 Dynamic simulation parameters) as well as the same constructions of the building envelope. Results indicate that the temperature varies between 17°C to 19°C during the winter which, aside from specific personal preferences, would require some heating. On the other hand, the temperature in the summer months rises above the simulation setpoint of 25°C which can be defined as too warm and would require cooling. All graphs show an average increase of 2°C of the temperature in the optimized insulated cases and no significant change in the energy-efficient windows case. This leads to the conclusion that albeit somewhat effective during the winter, the optimization changes do not eliminate the necessity for cooling of the houses in the summer months as well as some heating during the winter months.

Operative temperature as stated before takes into account the air speed and results are shown in Figure 34 to Figure 38. They indicate that the operative temperatures are slightly lower in the colder months and slightly higher in the summer months (± 1°C) in comparison to the air temperatures. Considering the fact that operative temperature is used as a simplified measure of thermal comfort (ASHRAE, 2020), those results once again express the necessity for heating during the winter and cooling during the summer months.

## 4.2 Relative humidity

Relative humidity results are shown in Figure 39 to Figure 43. Similar to the temperature results, the relative humidity graphs are almost the same for each house which can once again be explained with the corresponding building envelope constructions and the similar indoor conditions. Although the city of Plovdiv is situated along the Maritsa river the climate is relatively dry. The results show that the average relative humidity for each month in the houses is less than 50% with the exception of the data for April and October in the uninsulated cases of each house. They also indicate a slight decrease in the relative humidity levels in the insulated cases compared to the uninsulated ones. As stated before, high humidity levels block the evaporation of sweat and are problematic for warmer environments. Considering the climate of Plovdiv, the resulted relative humidity works well for the indoor comfort as well as the wooden construction of the houses as very high humidity can damage the integrity of the construction.

## 4.3 Annual heating load

The annual heating load is a main part of buildings' energy classification. Figure 44 to Figure 48 illustrate the simulated results for each building's five cases. In those graphs a line showing the difference in percentage between the base case scenario and the other four optimized cases can be seen. According to the Bulgarian regulations (Figure 28) buildings are classified based on their "*gross energy demand equivalent to the so-called primary energy*" (Ministry of regional development and public works, 2015) which includes the energy necessary for the conditioned volume's indoor microclimate to be kept within the comfort threshold, the heat losses and gains, the conversion, transmission and distribution of energy in building systems, the energy for transportation for heat and cold carriers (heat pumps, ventilators, etc.) as well as the energy required for the operation of other building systems (lighting, domestic water heating, etc.). As the buildings were simulated according to their condition during the Revival period, all those building systems included in the necessary calculations were simply not included in the parametric models and the results respectively. This makes it difficult to classify the buildings according to the Bulgarian energy certification but for the sake of comparison between the base cases and the optimized cases the example houses are classified according to the Austrian energy certification standards (Österreichisches Institut für Bautechnik, 2015) which categorize the buildings according to their heating demand.

As member states of the European Union and countries with relatively similar climate and considering the European regulatory requirements for energy classification of buildings, the norms are believed to be very similar so drawing a parallel between both certificates is justified.

All buildings' base cases can be classified with Class C with annual heating demand between 50 kWh.m$^{-2}$.a$^{-1}$ and 100 kWh.m$^{-2}$.a$^{-1}$ (Österreichisches Institut für Bautechnik, 2015). The second case with the change of the windows to energy efficient ones brings an average improvement of 13.6% which shows the great impact fenestration has on the heating load of a building. More significant change can be seen in the other three cases where the opaque building elements were insulated. The sheep wool case brings an average change of 66.5% and the hemp wool and the EPS case both come to 65.5% of average change. This shows the effect insulation has on heating and the importance of providing the best possible insulation for obtaining maximum thermal comfort. All three insulation cases bring up the buildings' classes to B with annual heating demand between 25 kWh.m$^{-2}$.a$^{-1}$ and 50 kWh.m$^{-2}$.a$^{-1}$, with the exception of the Dimitar Georgiadi house which comes up to Class A with annual heating load between 15 kWh.m$^{-2}$.a$^{-1}$ and 25 kWh.m$^{-2}$.a$^{-1}$ (Österreichisches Institut für Bautechnik, 2015)

Figure 44 represents the annual heating load of house Hindlyan. Replacing the windows with energy efficient ones in this house brings a reduction of the annual demand of 13% and more specifically 12.29 kWh.m$^{-2}$.a$^{-1}$. Sheep wool insulation has the biggest impact on heating load reduction in house Hindlyan – 66% and roughly 61 kWh.m$^{-2}$.a$^{-1}$, compared to the hemp wool and EPS cases which both reduce the heating load with 65% and roughly 60 kWh.m$^{-2}$.a$^{-1}$.

House of Dr. Stoyan Chomakov, as displayed in Figure 45, shows 7.76 kWh.m$^{-2}$.a$^{-1}$ reduction of heating load in the EEW case or 10% compared to the base case. As in house Hindlyan, the sheep wool case has the biggest saving of heating energy per year – 49.08 kWh.m$^{-2}$.a$^{-1}$ or 62% difference in comparison with the base case. Almost the same difference show the hemp wool and the EPS cases – approximately 48.5 kWh.m$^{-2}$.a$^{-1}$ and 61%.

Illustrated in Figure 46 are all cases of the Lamartine house. The reduction of the heating load in the EEW case is about 14% compared to the base case or 12.99 kWh.m$^{-2}$.a$^{-1}$. The sheep wool case and the hemp wool case both show a change of 58% with the sheep wool providing a slightly higher reduction of 54.05 kWh.m$^{-2}$.a$^{-1}$, compared to the base case than the hemp wool insulation which provides 53.45

kWh.m$^{-2}$.a$^{-1}$ reduction. EPS as in the other houses has the smallest impact out of the three insulation materials providing a reduction of 53.04 kWh.m$^{-2}$.a$^{-1}$ or 57% compared to the base case.

Figure 47 shows the heating load for the Dimitar Georgiadi house. As displayed in the graph the EEW case shows 14.35 kWh.m$^{-2}$.a$^{-1}$ difference compared to the base case which in percentage is roughly 15%. The greatest difference, just as in the other houses, comes from the sheep wool case – 79% or 73.89 kWh.m$^{-2}$.a$^{-1}$ reduction. The hemp wool and EPS cases both make approximately 78% difference in the annual heating demand (73 kWh.m$^{-2}$.a$^{-1}$ for the hemp wool case and 72.74 kWh.m$^{-2}$.a$^{-1}$ for the EPS case). All improved cases of Dimitar Georgiadi house provide bigger changes to the base case compared to all other houses which comes from both the larger fenestration area as well as the number of oriels and differences in the levels of the same floors. Shading also plays a major role in the heating load as this is the only house that is positioned in a densely packed area without lots of space around it.

As illustrated in Figure 48, the EEW case of Kuyumdzieva house provides 12.17 kWh.m$^{-2}$.a$^{-1}$ difference compared to the base case or 16%. Sheep wool again allows for more reduction in the heating load than the other chosen insulation materials – it reduces the demand with 67% (51.90 kWh.m$^{-2}$.a$^{-1}$) compared to the hemp wool which provides slightly less reduction (67% and 51.58 kWh.m$^{-2}$.a$^{-1}$) and the EPS which allows 66% reduction of the heating load (51.29 kWh.m$^{-2}$.a$^{-1}$).

## 4.4 Internal gains

Internal gains are identical in each house’s five cases due to the same input variables for the internal conditions in the simulations as stated in Table 6. The internal gains for all five examined buildings are illustrated in Figure 49. The internal conditions variables are set per m$^2$ of area which is the reason behind the differences in the amounts of internal gains between the houses. They also vary from month to month depending on the number of days in the month.

The monthly internal gains for the Hindlyan house vary between 2019 kWh and 2245 kWh for its 610 m$^2$ of gross heated area. Monthly internal gains for the Dr. Stoyan Chomakov house are in the range between 2513 kWh and 2788 kWh for its 691 m$^2$ of gross heated area. The smallest one of the houses - Lamartine house, has monthly internal gains varying between 1931 kWh and 2148 kWh for its 583 m$^2$

of gross heated area. The monthly internal gains for the Dimitar Georgiadi house vary between 2677 kWh and 2973 kWh for its 756 m$^2$ of gross heated area. The last of the houses and the biggest one – Kuyumdzieva, has monthly internal gains in the range between 3846 kWh and 4268 kWh for its 1053 m$^2$ of gross heated area. Those numbers demonstrate the differences in the results for each house and its connection to the gross area. The results obtained from this simulation are directly sequential to the parameters used for the simulation (Table 6) which are selected based on research on similar buildings, not on the actual internal conditions of the examined houses due to the fact that they are part of the Bulgarian national heritage and are currently used as museums, therefore number of occupants and other parameters are assumptions and not current reality.

## 4.5 Solar gains

Solar gains are an influential factor for obtaining thermal comfort. They directly influence the thermal load and can be very beneficial during the winter months. The amount of solar gains depends on the area and type of fenestration which is why the base case of the buildings is very different compared to the other four cases where the windows are the same energy efficient type. Results are illustrated in Figure 50 to Figure 54 in Chapter 3.5. They show that the highest amount of solar gains occurs in August and the lowest amount – in December which is normal for a country in the northern hemisphere. The monthly amount of solar gains for the base case with single pane windows vary between 1447 kWh and 4102 kWh for the Hindlyan house, between 1083 kWh and 3697 kWh for the Dr. Stoyan Chomakov house, between 1524 kWh and 4200 kWh for the Lamartine house, between 2214 kWh and 5943 kWh for the Georgiadi house and between 3158 kWh and 7317 kWh for the Kuyumdzieva house. In the other cases with energy efficient windows results vary between 1125 kWh and 3155 kWh for the Hindlyan house, between 839 kWh and 2850 kWh for the Dr. Stoyan Chomakov house, between 1186 kWh and 3242 kWh for the Lamartine house, between 1726 kWh and 4559 kWh for the Georgiadi house and between 2472 kWh and 5615 kWh for the Kuyumdzieva house. The calculated difference between the cases is 22% on average which means that approximately 22% reduction of the solar gains happens when replacing the old single pane windows with energy efficient double pane ones.

## 4.6 Transmission losses

Transmission losses happen through conduction through the building envelope. The simulated results for each of the houses' five cases are shown in Figure 55 to Figure 59. In each of the graphs it is visible that there is reduction of transmission losses between the base case and the EEW case in the colder months which means that solely changing the windows with energy efficient ones can lead to some improvement and more specifically 5% difference in the case of the Hindlyan house, 3% difference for the Dr. Stoyan Chomakov house, 5% difference for the Lamartine house, 6% difference for the Georgiadi house and 5% difference for the Kuyumdzieva house compared to their base cases. More substantial difference can be seen in the other cases with the thermally improved opaque building elements. The results for Hindlyan house show improvement with 59% reduction of the transmission losses in the sheep wool case compared to the base case, as well as 58% difference in the hemp wool case and 57% difference in the EPS case. The same difference in percentage can be seen in the Dr. Stoyan Chomakov house compared to its base case. For the Lamartine house a significant improvement of 67% in the sheep wool case as well as 66% in the hemp wool case and the EPS case compared to its base case can be seen in Figure 57. House of Dimitar Georgiadi shows 61% progress when it comes to the sheep wool case and 60% progress in the hemp wool and EPS cases compared to its base case. And the biggest one of the houses – Kuyumdzieva house shows a 57% difference in the sheep wool case and 56% in the hemp wool and EPS cases compared to its base case. Those differences are very obvious in the graphs in Chapter 3.6. It is important to mention that the Lamartine house which shows the highest percentage of difference to its base case is the only house without an unheated basement which explains the greater difference compared to the other houses who have much closer numbers. The percentages also show that the sheep wool provides the biggest progress compared to the other two explored types of insulation – hemp wool and EPS. This is due to the fact that sheep wool has the lowest thermal transmittance (U-value) of the selected insulation materials and lower transmittance results in lower amounts of transmission losses - sheep wool has a U-value of 0.0385 $W.m^{-2}.K^{-1}$, hemp wool has a U-value of 0.04 $W.m^{-2}.K^{-1}$ and EPS has a U-value of 0.041 $W.m^{-2}.K^{-1}$.

## 4.7 Air change losses

The losses due to air change are calculated on a monthly basis for each of the five example houses. The input parameters for the infiltration and ventilation are the same for each house (Table 6, Table 7 and Table 8) so that the difference in the results between the houses comes solely from the difference in their volumes. As visible in the graphs (Figure 60 to Figure 64) the losses due to air change are higher in the winter months and lower in the summer months due to the higher temperature difference in the winter between the indoors and outdoors. The graphs also visualize quite well the difference in air change losses between the insulated cases and the uninsulated ones. During the colder months the insulated cases have higher amounts of air change losses as for example in April and October which are season transitioning months there is a difference of approximately 1000 kWh. This is due to the temperature differences between interior and exterior and the fact that the insulated cases show higher indoor temperatures during the winter months. On the other hand, in the summer months the insulated cases show lower amounts of air change losses compared to the uninsulated ones due to the fact that the outdoor temperature is not so much lower than the indoor one as it is in the winter.

## 4.8 Summer overheating

As uncomfortable as cold temperatures can be, overheating can also be a problem for the thermal comfort in buildings. The necessity for cooling has grown substantially in the past years as temperatures rise each year. Overheating can be considered as a problem of the present since it has become worrisome for Europe only about 30 years ago. As stated before, Bulgarian norms do not have exact temperature ranges for regulating thermal comfort. For the simulation purposes the comfortable range was chosen to be between 18°C and 26°C, and 22°C as the maximum indoor temperature above which ventilation is necessary. Temperature levels above 26°C would be considered overheating for the purposes of this research although this excludes the human seasonal heat adaptation and the change in perception of temperature.

Figure 65 illustrates the cooling load of house Hindlyan. With the exception of April and October when the temperature has many fluctuations, only the winter months require extensive heating which means that the temperature is within the comfortable ranges almost all the time during the other seven months. Insulating the thermal envelope provides severe decrease in the heating load (7000 kWh monthly on average in the winter months – November till March) and some decrease in the cooling load (3000 kWh on average in the seven months that require cooling – from April till October). This shows that the problem of overheating cannot be solved solely by improving the thermal envelope of the building. The biggest need for cooling happens in June, July and August when according to Figure 34 the average operative temperature rises above 26°C. During those months the temperature rises above 26°C with half a degree on average which means that more natural ventilation and shading could fix the problem as a more sustainable solution, compared to mechanical ventilation systems who are needed when the temperature rise is more tangible.

Similar behavior can be seen in Figure 66 depicting the cooling load of Dr. Stoyan Chomakov house. Approximately 6500 kWh less on average are needed to heat the house during the winter months which makes insulation an efficient way to improve thermal comfort in the winter but in other seasons insulation by itself fails to provide the desired comfort. The decrease of the cooling load in the insulated cases can be averaged to 2100 kWh during the seven warmer months which is a good amount but not enough for this to be a complete solution by itself, especially in July when the cooling demand is at its highest (4000 kWh on average in the insulated cases). As visualized in Figure 35 operative temperatures above 26°C happen in July and August growing with less than half a degree which gives the opportunity for the problem to be fixed more sustainably as stated before – with more natural ventilation and shading.

Shown in Figure 67 are the cooling loads of Lamartine house. The summer months require close to none heating but cooling is a necessity during all seasons except for the winter. In those months by insulating the building envelope an average of 3000 kWh less energy would be needed to cool down the house to a comfortable temperature. The cooling demand is at its highest in July and August and the temperatures in those months also go above 26°C (Figure 36) but once again with half a degree on average which could be fixed relatively easy. It is important to be said that in the insulated cases (SW, Hemp and EPS) the temperature rise above 26°C is a little higher than the one in the base case and the energy efficient windows case because of the increased compactness of the building envelope.

Figure 68 illustrates the cooling loads of the Dimitar Georgiadi house. Results show that an average of 4000 kWh can be saved from cooling during the seven warmer months. The amount of energy that could be saved with insulation is much higher than the buildings discussed above due to the much bigger volume of the house as well as the oriels and level differences of the house which complicate the geometry and increase the heating and cooling demands in the base case. According to Figure 37 temperature above 26°C occurs in July and August in the base case and the EEW case and in the insulated cases June and September also have temperature above 26°C, all crossing the threshold with roughly half a degree.

The cooling loads of the Kuyumdzieva house are depicted in Figure 69. A possible reduction of roughly 3000 kWh cooling load is possible in the warmer months by insulating the thermal envelope with any of the chosen insulating materials. Like in the previous house the cooling load is higher than the first three houses because this is the biggest one of all, thus it has the largest conditioned volume. Temperature above 26°C happens in July and August in the base case and the EEW case, and in the insulated cases the June and September operative temperatures also cross the threshold but as in the other buildings – only by half a degree on average.

Considering all results overheating doesn't seem to pose a great threat to the possible inhabitants of the houses. During the summer months which are the problematic ones in terms of overheating the average temperature rises above the 26°C threshold only by half a degree on average. Mitigating solutions are possible to be sustainable and relatively easy. Considering the above-mentioned human perception of temperature and the adaptation that happens during each season can sometimes make even 27°C comfortable, which although varying between people, could mean that the evaluated buildings do not pose any overheating threats. Replacing the windows with energy efficient ones does not make too big of a difference in terms of cooling and heating loads but insulation brings higher reduction and helps with containing the temperature levels inside the houses in a relatively comfortable range.

## 4.9 Daylight analysis

Daylight is one of the most impactful factors when talking about building comfort. Nowadays people even evaluate buildings based on the amounts of daylight available inside. It is now known that severe lack of daylight leads to health issues and depression. Daylight is a key factor for healthy indoor environment and is an important task in building design. According to CIBSE, buildings with average daylight factor in the range of 4% > DF ≥ 2% are medium daylit and average DF ≥ 5% creates a strongly daylit building (The Chartered Institution of Building Services Engineers, 2015).

Results in Chapter 3.9 show the daylight factor and illuminance levels calculated for each floor of the examined buildings. According to them each buildings' ground floors are not as well-lit as the upper floors. This is due to the fact that ground floors are usually more shaded on account of the city context the buildings are situated in as well as the smaller window area caused by the fear of foray encompassing households during the Revival period.

Average daylight factors for House Hindlyan show medium levels of daylight (Table 12) but the percentage of test points where the DF is higher than 2% is insufficient (~38% for Ground floor and ~59% for First floor). This means that artificial light is necessary almost everywhere for specific tasks. Average illuminance levels shown in Figure 70 provide an overview of the amounts of daylight available for a representative date and time each month. Although the results do not show each day and time throughout the year, the provided ones can be used to conclude the sufficiency of daylight for the test-point surface. Bulgarian standards determine 200 lux as a minimum threshold for illuminance levels in residential buildings (Ministry of national health, 1976). Table 11 shows the percentage of test points where the illuminance levels are above 200 lux. Despite the winter months in the ground floor, all results show that more than 50% of the test points have illuminance levels of more than 200 lux. This creates a good indoor environment but considering that it is not 100% of the points that show these results – artificial light is necessary for some tasks.

Similar results can be seen in the other four examined houses. The Dr. Stoyan Chomakov house shows medium levels of daylight as well (Table 14) but the percentage of test points with DF higher than 2% is completely insufficient (~28% for Ground floor and ~37% for First floor). According to Table 13 the test points with illuminance higher than 200 lux go above 50% only in the summer months for both cases. This means that artificial light is necessary almost everywhere.

Lamartine house has three floors and only the first and the second are sufficiently daylit resulting in 80% on average for the second floor and 70% on average for the first floor of test points where the illuminance goes above 200 lux. The ground floor shows insufficient daylight where test points with illuminance above 200 lux go below 50% even in the summer months which is again normal for houses from that period whose ground floors were built to hide people within the house and have as little windows as possible. The insufficiency of daylight in the ground floor can be seen also in Table 16 showing the percentage of test points with DF higher than 2% (~19% for Ground floor, ~56% for First floor and ~68% for Second floor).

Dimitar Georgiadi house also has three floors but the ground floor here is much better lit compared to the Lamartine house. Test points with illuminance above 200 lux come to roughly 70% of all in the ground floor, about 92% on average for the first floor and 93% for the second floor according to Table 17. The percentage of test points with DF higher than 2% (~43% for Ground floor, ~68% for First floor and ~71% for Second floor) is shown in Table 18 and also gives an overview of the good daylight situation of Dimitar Georgiadi house.

Medium levels of daylight can also be assumed for Kuyumdzieva house which is supported by the results shown in Table 19 and Table 20. Approximately 52% of the ground floor test points and roughly 54% of the first-floor test points have DF higher than 2% as well as 72% on average of the ground floor test points and 70% of the first-floor test points show illuminance levels above 200 lux. Kuyumdzieva house has a good number of windows but the problem here comes from the spaces that are too big for daylight to be comfortable enough.

Overall, the five buildings show medium daylight levels with the upper floors much better lit than the ground floors. Each building was simulated in two cases with the two different types of windows – the basic single pane ones and energy efficient ones – which do have some difference between each other but not nearly enough for one to be considered better (roughly 0.05% difference on average between the test points in both cases). Considering the fact that the EEW case is reviewed as a fitter option for providing better thermal comfort in the buildings, it could be concluded that energy efficient windows are the stronger option for visual comfort in the buildings as well since results show that they provide the same amount of daylight as the single pane windows case.

## 4.10 Results reliability

The accuracy of any results can be compromised by different factors. Firstly, simulation results depend on using specific conditions such as weather parameters which do not change during the simulation process. In reality, the weather file that was used for this research contains data from previous years (usually a mixture of satellite data and ground collected data) which is calculated on a specific timestep-based method and the results for moments in-between the timestep are usually statistically assigned using probability distribution. This creates a weather model which is almost very accurate but the weather conditions cannot be 100% the same as they would be experienced in reality. Secondly, for the purposes of this research some specific software was used which always has its limitations. In the case of EnergyPlus (International collaboration team, 2020), which was used for all thermal evaluations, the program struggles with doing calculations on a model with too many faces which is almost always the case when evaluating historic buildings. The buildings' design includes many oriels, different roof elements as well as waved geometry which cannot be calculated if the model is 100% accurate regarding architectural design. This leads to the necessity of the simplification of the model geometry which inevitably creates gaps between reality and simulation. Additionally, geometry and material data on the examined buildings consists of an old research led in the 1950s which was based on on-site measurement. Considering the fact that at that time accurate measuring technology was not available, those plans cannot be believed to be incredibly precise. Lastly, construction materials used for the purposes of this study (Chapter 2.6) are the same for each evaluated building. Although this fact is known from the buildings' owners, the thicknesses of the layers of the construction elements may vary because of the used wooden construction elements which at that time were cut by hand and are not pre-produced with the exact same sizes by a machine as they would be nowadays. Even though those differences are probably small, they would make a difference in the results concerning U-values of construction elements leading to difference in the performance results of each building.

Although all previously explained parameters were used in a way so that they provide maximum truthfulness to the results, all these factors should be considered as possible sources of error.

# 5 CONCLUSION

The main purpose of this research is to evaluate whether the Plovdiv vernacular buildings from the Bulgarian Revival period perform well in current weather context and can respond to the modern requirements for energy efficiency and building comfort. The buildings from that time are considered as national heritage and are identified as sustainable from the architectural community in Bulgaria. The five evaluated buildings that are part of this study were carefully selected to be appropriate examples of the typical Plovdiv Revival building. Parametric simulations were carried out for each house in their base case as well as four optimized cases – exchanging the windows with energy efficient ones and insulating the thermal envelope with sheep wool, hemp wool and EPS respectively. Since the buildings are considered sustainable because of their construction comprising of local natural materials, the choice of natural insulating materials is completely in accordance – sheep wool and hemp wool are available in Bulgaria and require a lot less energy for yield compared to other insulating materials (Georgiev, 2015) such as EPS for example which was chosen only for the purpose of comparison as it is currently one of the most popular insulating materials.

Overall, the houses exhibit satisfactory level of performance in their base cases, as their simulated annual heating loads put them in Energy Class C (Österreichisches Institut für Bautechnik, 2015). Indoor temperatures are within the comfortable range with the exception of the winter months when heating is necessary. The EEW proposed case which represents the buildings with their single pane windows replaced by energy efficient ones, provides some reduction of the energy losses as well as some improvement in the heating and cooling demands but the biggest impact on the performance have the insulated cases. The three cases with addition of insulation to the building elements show similar results but the sheep wool insulation runs a step before with an average change of 66.4% in the heating load and roughly 60% less transmission losses compared to the base cases. In general, the insulated cases allow for significant reduction of transmission losses and air change losses and more than 58% less heating load in each house. The results also show that the possibility of summer overheating exists, especially with the added insulation where indoor temperatures are very slightly higher than the uninsulated cases but the problem could be addressed in relatively easy and sustainable manner or ignored completely considering the different perception of temperature between seasons.

In terms of visual performance, the sufficiency of daylight was assessed showing that the ground floors are generally darker than the upper floors which comes not only from the environmental context and shading but was a deliberate decision of the master builders during the Revival period with the idea that the ground floors would have stone masonry construction and as little window area as possible in order to protect the inhabitants from foray during the Ottoman slavery (Daskalov, 2004). Another reason for the lack of enough daylight among the example buildings' entire volume is their sizes. The grandiose architecture was influenced by the owners' desire to show splendor and the master builders' eagerness to explore architectural possibilities but the volume of the rooms in each one of the houses is simply too big for them to be sufficiently lit only by the daylight coming through the windows. Moreover, explored were the two window types for each building and the results show very similar data which means that no matter the type of windows, artificial light would still be necessary for some tasks.

This study demonstrates the advantages of thermal insulation for building performance and its role to providing thermal comfort but also illustrates the fact that the Plovdiv Revival buildings do meet the current building performance requirements in their current states as well. The results prove that with some adjustments those buildings can easily come to Energy Class B making them fully competitive to the contemporary ones although such changes should be carefully thought and adjusted to their architecture keeping in mind that the buildings are part of the National Cultural Institute's list of vernacular heritage buildings. Furthermore other buildings from that period could be studied and compared between regions since the same construction is known to be thicker in order to provide comfort without insulation in the colder zones of Bulgaria (Petrov, 2014). Moreover, simulation results could be compared to monitored ones in buildings which are currently still used as residential ones. Lastly, the building practices from the Revival period could be further assessed with the opportunity to implement them in new multi-storey buildings as well as explore the possibilities to make them as energy efficient and sustainable as possible from the very beginning.

# 6 INDEX

## 6.1 List of Figures

## 6.2 List of Tables

## 6.3 List of Equations

# 7 REFERENCES

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# 8 APPENDIX

## A. Zoning

- Zoning of House Hindlyan

| Zone number/name | Area (m$^2$) | Volume (m$^3$) |
|---|---|---|
| Ground floor | Height 3.1 m | |
| 1 | 42.40 | 128.12 |
| 2 | 13.16 | 40.8 |
| 3 | 26.77 | 80.95 |
| 4 | 10.62 | 32.92 |
| 5 | 51.8 | 160.58 |
| 6 | 21.94 | 68.01 |
| 7 | 26.16 | 81.1 |
| 8 | 35.75 | 110.83 |
| 9 | 28.55 | 88.52 |
| 10 | 27.49 | 85.23 |
| 11 | 17.15 | 53.18 |
| 12 | 28.69 | 88.94 |
| First floor | Height 3.7 m | |
| 13 | 51.57 | 190.81 |
| 14 | 11.76 | 43.51 |
| 15 | 34.32 | 126.99 |
| 16 | 7.82 | 28.94 |
| 17 | 74.55 | 275.84 |
| 18 | 22.95 | 84.91 |
| 19 | 47.7 | 176.49 |
| 20 | 28.84 | 106.71 |
| Roof (unconditioned) | Height 1.0 m | |
| 21 | 279.51 | 279.51 |

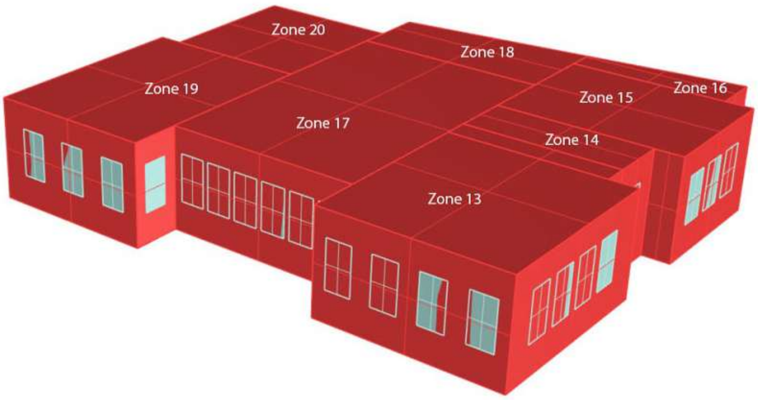

*Figure 87 Zones Hindlyan house - first floor*

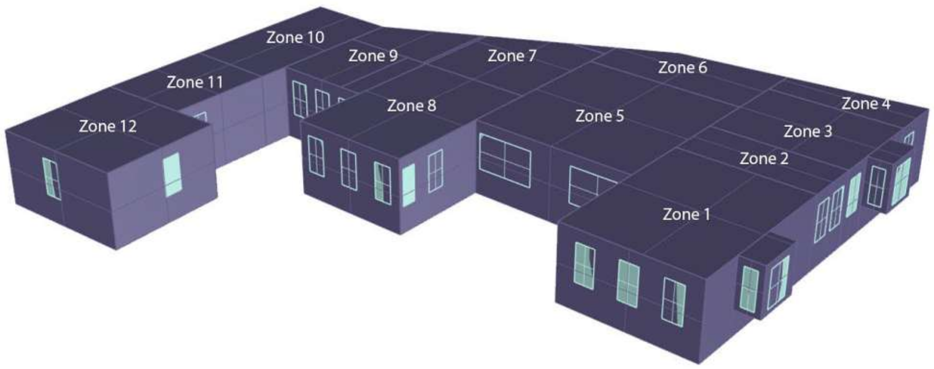

*Figure 88 Zones Hindlyan house - ground floor*

- Zoning of House of Dr. Stoyan Chomakov

| Zone number/name | Area ($m^2$) | Volume ($m^3$) |
|---|---|---|
| Basement (unconditioned) | Height 2.5 m | |
| 0 | 313 | 782.5 |
| Ground floor | Height 3.4 m | |
| 1 | 24.01 | 81.65 |
| 2 | 24.75 | 84.15 |
| 3 | 16.00 | 54.40 |
| 4 | 34.20 | 116.28 |
| 5 | 22.10 | 75.14 |
| 6 | 9.43 | 32.05 |
| 7 | 41.93 | 142.55 |
| 8 | 28.70 | 97.58 |
| 9 | 69.00 | 234.60 |
| 10 | 34.20 | 116.28 |
| 11 | 22.10 | 75.14 |
| 12 | 51.35 | 174.59 |
| First floor | Height 4.15 m | |
| 13 | 34.20 | 141.93 |
| 14 | 22.10 | 91.72 |
| 15 | 9.43 | 39.11 |
| 16 | 41.93 | 173.99 |
| 17 | 53.25 | 221.00 |
| 18 | 44.48 | 184.46 |
| 19 | 34.20 | 141.93 |
| 20 | 22.10 | 91.72 |
| 21 | 51.35 | 213.10 |
| Roof (unconditioned) | Height 1.0 m | |
| 22 | 313 | 313 |

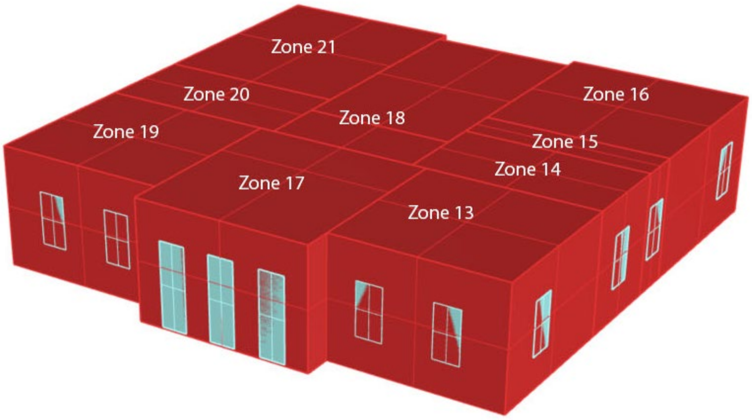

*Figure 89 Zones of House of Dr. Stoyan Chomakov – first floor*

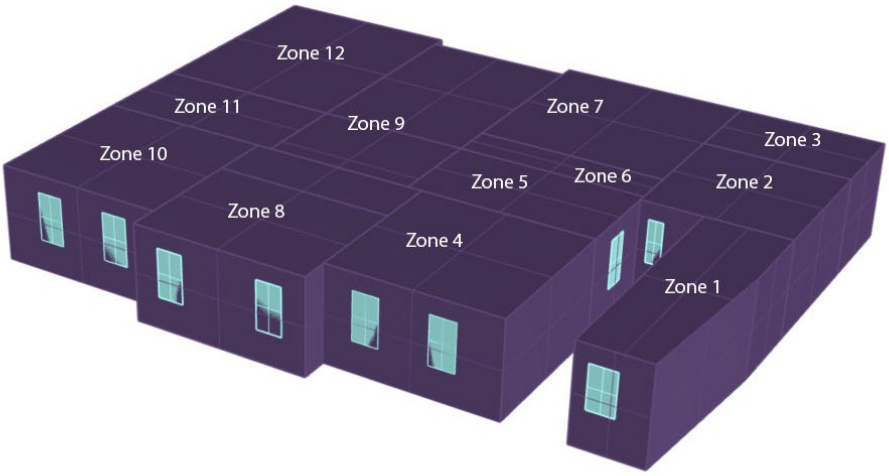

*Figure 90 Zones of House of Dr. Stoyan Chomakov – ground floor*

- Zoning of House of Georgi Mavridi (Lamartine house)

| Zone number/name | Area (m$^2$) | Volume (m$^3$) |
|---|---|---|
| Ground floor | Height 2.35 m | |
| 1 | 43.85 | 103.05 |
| 2 | 40.45 | 95.06 |
| 3 | 19.39 | 45.57 |
| 4 | 18.85 | 44.29 |
| 5 | 13.33 | 31.33 |
| 6 | 9.61 | 22.59 |
| 7 | 13.66 | 32.10 |
| 8 | 18.80 | 44.17 |
| 9 | 10.64 | 25.01 |
| 10 | 16.76 | 39.38 |

| | | |
|---|---|---|
| First floor | Height 3.5 m | |
| 11 | 43.90 | 153.66 |
| 12 | 17.43 | 60.99 |
| 13 | 26.48 | 92.68 |
| 14 | 47.28 | 165.43 |
| 15 | 18.04 | 63.13 |
| 16 | 6.88 | 24.08 |
| 17 | 24.46 | 85.61 |
| Second floor | Height 3.7 m | |
| 18 | 43.90 | 162.44 |
| 19 | 17.43 | 64.48 |
| 20 | 30.10 | 111.37 |
| 21 | 47.28 | 174.89 |
| 22 | 19.54 | 72.30 |
| 23 | 7.38 | 27.32 |
| 24 | 27.79 | 102.80 |
| Roof (unconditioned) | Height 1.0 m | |
| 25 | 193.41 | 193.41 |

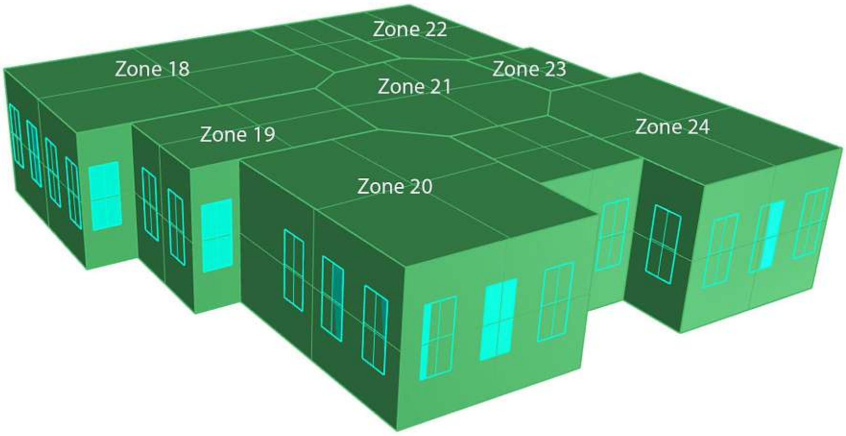

*Figure 91 Zones of House of Georgi Mavridi (Lamartine) – second floor*

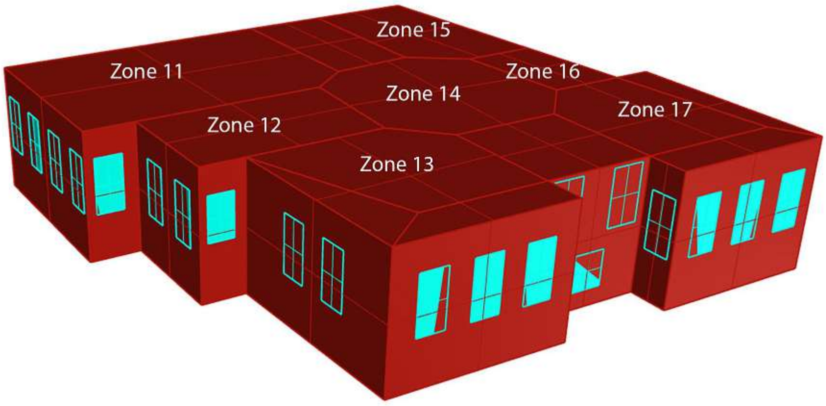

*Figure 92 Zones of House of Georgi Mavridi (Lamartine) – first floor*

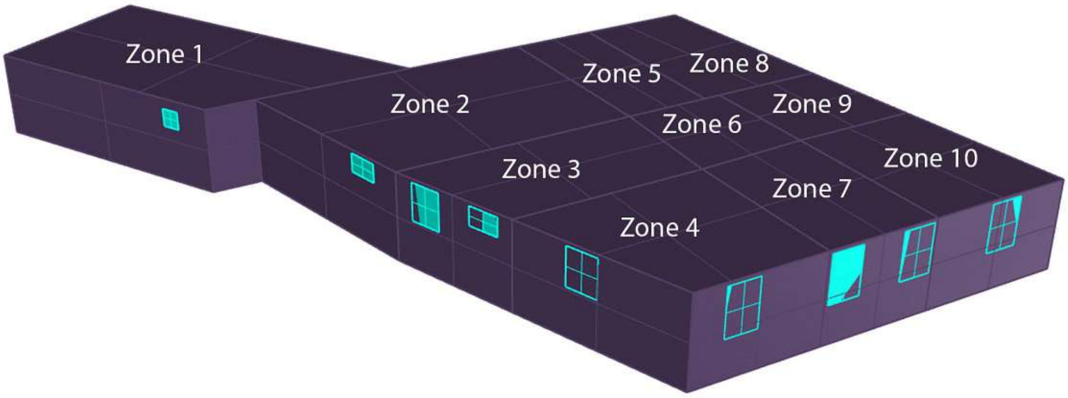

*Figure 93 Zones of House of Georgi Mavridi (Lamartine) – ground floor*

- Zoning of House of Dimitar Georgiadi

| Zone number/name | Area (m$^2$) | Volume (m$^3$) |
|---|---|---|
| Basement (unconditioned) | Height 2.5 m | |
| 0 | 238.54 | 596.35 |
| Ground floor | Height 3.8 m | |
| 1 | 38 | 141.43 |
| 2 | 36.54 | 138.85 |
| 3 | 97.16 | 381.26 |
| 4 | 36.88 | 140.12 |
| 5 | 31.95 | 121.42 |
| First floor | Height 3.3 m | |
| 6 | 41.53 | 137.04 |
| 7 | 17.38 | 57.34 |
| 8 | 36.13 | 119.24 |
| 9 | 69.96 | 222.91 |
| 10 | 42.56 | 140.44 |
| 11 | 16.01 | 52.83 |
| 12 | 32.91 | 107.30 |
| Second floor | Height 4.1 m | |
| 13 | 41.53 | 170.26 |
| 14 | 17.38 | 71.25 |
| 15 | 36.13 | 148.15 |
| 16 | 69.96 | 278.88 |
| 17 | 42.56 | 174.48 |
| 18 | 16.01 | 65.64 |
| 19 | 35.89 | 147.17 |
| Roof (unconditioned) | Height 1.0 m | |
| 20 | 259.46 | 259.46 |

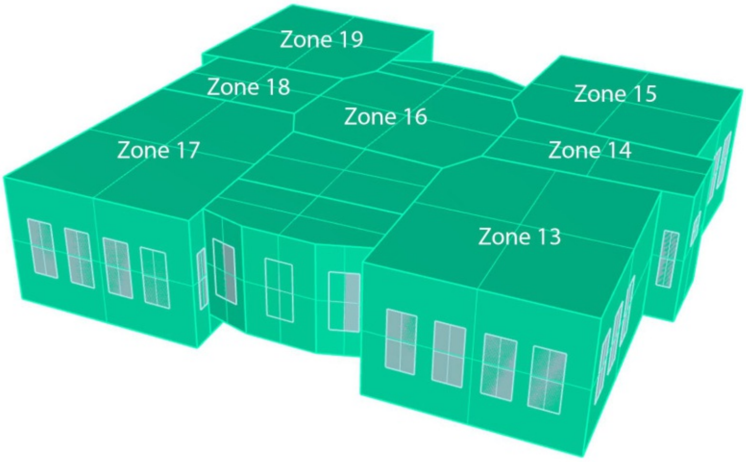

*Figure 94 Zones of House of Dimitar Georgiadi – second floor*

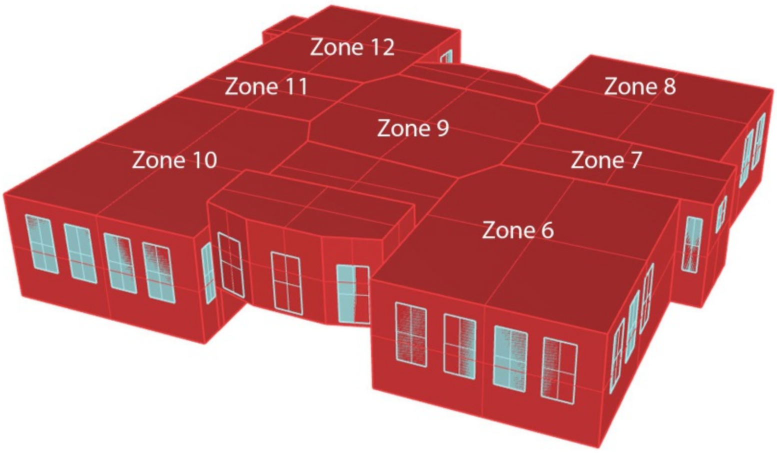

*Figure 95 Zones of House of Dimitar Georgiadi – first floor*

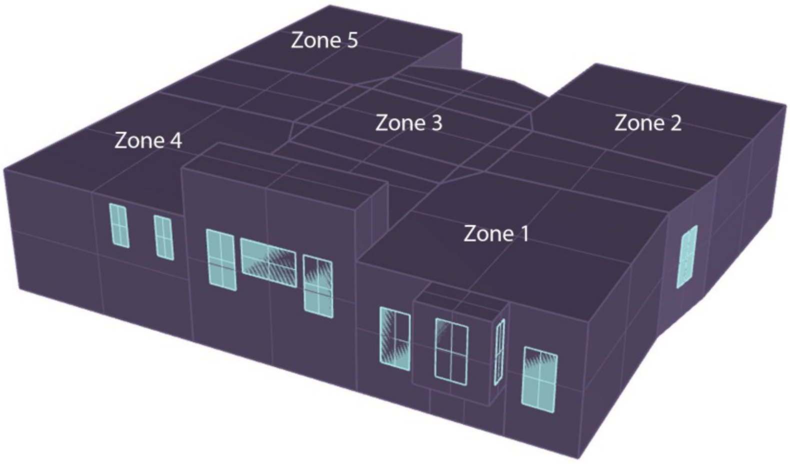

*Figure 96 Zones of House of Dimitar Georgiadi – ground floor*

- Zoning of Kuyumdzieva house

| Zone number/name | Area ($m^2$) | Volume ($m^3$) |
|---|---|---|
| Basement (unconditioned) | Height 6.0 m | |
| 0 | 497.38 | 2984.29 |
| Ground floor | Height 3.8 m | |
| 1 | 50.29 | 191.09 |
| 2 | 18.03 | 68.50 |
| 3 | 7.43 | 28.22 |
| 4 | 21.72 | 82.53 |
| 5 | 36.96 | 140.46 |
| 6 | 24.51 | 93.12 |
| 7 | 33.63 | 127.80 |
| 8 | 150.29 | 571.09 |
| 9 | 42.24 | 160.49 |
| 10 | 33.48 | 127.23 |
| 11 | 12.88 | 48.93 |
| 12 | 65.95 | 250.60 |
| First floor | Height 4.1 m | |
| 13 | 50.29 | 206.18 |
| 14 | 18.03 | 73.90 |
| 15 | 7.43 | 30.44 |
| 16 | 21.72 | 89.04 |
| 17 | 36.96 | 151.55 |
| 18 | 24.51 | 100.47 |
| 19 | 53.76 | 220.40 |
| 20 | 178.94 | 733.63 |
| 21 | 51.93 | 212.92 |
| 22 | 29.60 | 121.35 |
| 23 | 16.76 | 68.72 |
| 24 | 65.95 | 270.38 |
| Roof (unconditioned) | Height 1.0 m | |
| 25 | 555.85 | 555.85 |

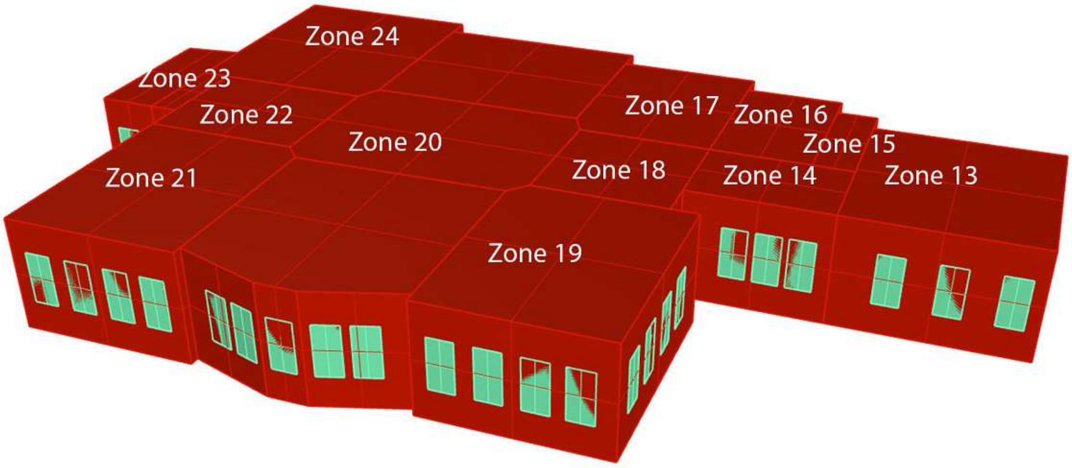

*Figure 97 Zones of Kuyumdzieva house – first floor*

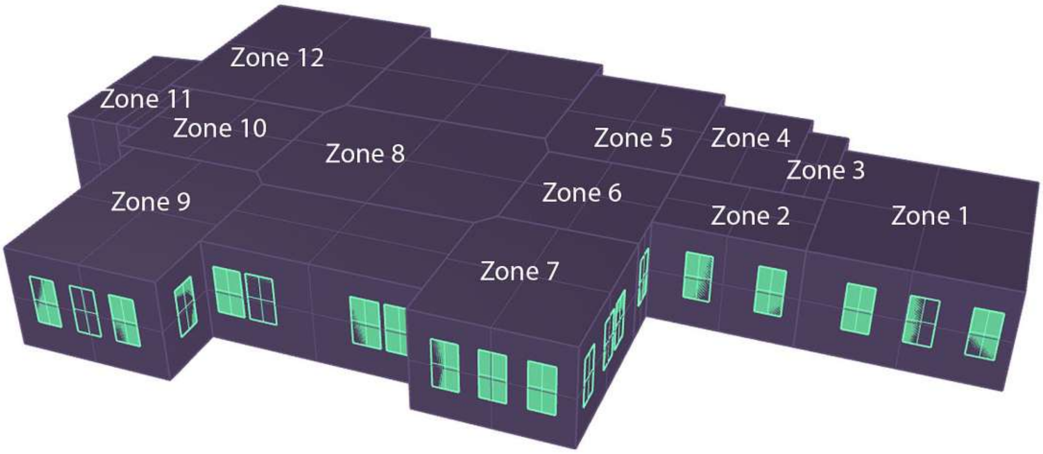

*Figure 98 Zones of Kuyumdzieva house – ground floor*

## B. Tables

All material layers of the construction elements are stated in the following tables..

All chosen buildings have almost the same constructions thus the tables refer to all buildings but are separated into cases.

*Table 21 Building construction material layers Base Case and Case EEW*

| | Layers of building element (1st layer is the outer-most one) | Thickness (m) d | Thermal conductivity $(W.m^{-1}.K^{-1})$ λ | Density $(kg.m^{-3})$ ρ | Specific heat capacity $(J.kg^{-1}.K^{-1})$ *c* |
|---|---|---|---|---|---|
| External wall – ground floor | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| External wall – upper floors | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Adobe bricks | 0.12 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| External wall – basement (where existing) | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| Floor to ground | Compacted ground | 0.5 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor/Ceiling | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Exposed floor | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |

| | | | | | |
|---|---|---|---|---|---|
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor to unheated basement (where existing) | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Ceiling to roof space | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Roof | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Air space | 0.15 | 0.025 | 1 | 1008 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | | | | | |
| | Layers of building element | Thickness (m) | Thermal transmittance (W.m$^{-2}$.K$^{-1}$) U | Solar heat gain coefficient SHGC | Visible transmittance VT |
| Window Base Case | Single pane glass | 0.006 | 4.8 | 0.81 | 0.89 |
| Window Case EEW | Low-E argon filled Dual pane glass | 0.028 | 1.48 | 0.685 | 0.79 |

*Table 22 Building construction material layers Case SW*

| | Layers of building element (1$^{st}$ layer is the outer-most one) | Thickness (m) d | Thermal conductivity (W.m$^{-1}$.K$^{-1}$) λ | Density (kg.m$^{-3}$) ρ | Specific heat capacity (J.kg$^{-1}$.K$^{-1}$) *c* |
|---|---|---|---|---|---|
| External wall – ground | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |

| | | | | | |
|---|---|---|---|---|---|
| floor | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Sheep wool with additional construction | 0.08 | 0.0385 | 100 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |
| External wall – upper floors | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Adobe bricks | 0.12 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Sheep wool with additional construction | 0.08 | 0.0385 | 100 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |
| External wall – basement (where existing) | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| Floor to ground | Compacted ground | 0.5 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Hydro-insulation | 0.001 | 0.17 | 600 | 1050 |
| | Sheep wool with additional construction | 0.08 | 0.0385 | 100 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor/Ceiling | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |

| | | | | | |
|---|---|---|---|---|---|
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Exposed floor | Fir cover | 0.03 | 0.13 | 600 | 1610 |
| | Sheep wool | 0.10 | 0.0385 | 100 | 1600 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor to unheated basement (where existing) | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Sheep wool | 0.10 | 0.0385 | 100 | 1600 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Ceiling to roof space | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Sheep wool | 0.10 | 0.0385 | 100 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Roof | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Air space | 0.15 | 0.025 | 1 | 1008 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| Roof – ground floor zones | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Sheep wool | 0.15 | 0.0385 | 100 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | | | | | |

| | Layers of building element | Thickness (m) | Thermal transmittance ($W.m^{-2}.K^{-1}$) U | Solar heat gain coefficient SHGC | Visible transmittance VT |
|---|---|---|---|---|---|
| Windows | Low-E argon filled Dual pane glass | 0.028 | 1.48 | 0.685 | 0.79 |

*Table 23 Building construction material layers Case H*

| | Layers of building element (1st layer is the outer-most one) | Thickness (m) d | Thermal conductivity ($W.m^{-1}.K^{-1}$) λ | Density ($kg.m^{-3}$) ρ | Specific heat capacity ($J.kg^{-1}.K^{-1}$) c |
|---|---|---|---|---|---|
| External wall – ground floor | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Hemp wool with additional construction | 0.08 | 0.04 | 80 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |
| External wall – upper floors | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Adobe bricks | 0.12 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Hemp wool with additional construction | 0.08 | 0.04 | 80 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |

| | | | | | |
|---|---|---|---|---|---|
| External wall – basement (where existing) | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| Floor to ground | Compacted ground | 0.5 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Hydro-insulation | 0.001 | 0.17 | 600 | 1050 |
| | Hemp wool with additional construction | 0.08 | 0.04 | 80 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor/Ceiling | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Exposed floor | Fir cover | 0.03 | 0.13 | 600 | 1610 |
| | Hemp wool | 0.10 | 0.04 | 80 | 1600 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor to unheated basement (where existing) | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Hemp wool | 0.10 | 0.04 | 80 | 1600 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Ceiling to roof space | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Hemp wool | 0.10 | 0.04 | 80 | 1600 |

| | | | | | |
|---|---|---|---|---|---|
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Roof | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Air space | 0.15 | 0.025 | 1 | 1008 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| Roof – ground floor zones | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Hemp wool | 0.15 | 0.04 | 80 | 1600 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | | | | | |
| | Layers of building element | Thickness (m) | Thermal transmittance ($W.m^{-2}.K^{-1}$) U | Solar heat gain coefficient SHGC | Visible transmittance VT |
| Windows | Low-E argon filled Dual pane glass | 0.028 | 1.48 | 0.685 | 0.79 |

*Table 24 Building construction material layers Case EPS*

| | Layers of building element (1st layer is the outer-most one) | Thickness (m) d | Thermal conductivity ($W.m^{-1}.K^{-1}$) λ | Density ($kg.m^{-3}$) ρ | Specific heat capacity ($J.kg^{-1}.K^{-1}$) *c* |
|---|---|---|---|---|---|
| External wall – ground floor | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | EPS with additional construction | 0.08 | 0.041 | 20 | 1260 |

| | | | | | |
|---|---|---|---|---|---|
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |
| External wall – upper floors | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Adobe bricks | 0.12 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | EPS with additional construction | 0.08 | 0.041 | 20 | 1260 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Plaster board | 0.015 | 0.21 | 700 | 1000 |
| External wall – basement (where existing) | Sand stone (river stones) | 0.7 | 2.3 | 2600 | 1000 |
| | Straw clay mixture | 0.02 | 0.6 | 1400 | 930 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| Floor to ground | Compacted ground | 0.5 | 1.02 | 1900 | 837 |
| | Straw clay mixture | 0.03 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Hydro-insulation | 0.001 | 0.17 | 600 | 1050 |
| | EPS with additional construction | 0.08 | 0.041 | 20 | 1260 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor/Ceiling | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Air space | 0.10 | 0.025 | 1 | 1008 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Exposed floor | Fir cover | 0.03 | 0.13 | 600 | 1610 |
| | EPS | 0.10 | 0.041 | 20 | 1260 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |

| | | | | | |
|---|---|---|---|---|---|
| | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| Floor to unheated basement (where existing) | Oak decking | 0.04 | 0.2 | 800 | 1610 |
| | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | EPS | 0.10 | 0.041 | 20 | 1260 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Ceiling to roof space | Sand cover | 0.02 | 2 | 1700 | 910 |
| | Straw and clay mixture | 0.14 | 0.6 | 1400 | 930 |
| | Oak planks | 0.02 | 0.2 | 800 | 1610 |
| | EPS | 0.10 | 0.041 | 20 | 1260 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir ceiling | 0.03 | 0.13 | 600 | 1610 |
| Roof | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | Air space | 0.15 | 0.025 | 1 | 1008 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| Roof – ground floor zones | Clay roof tiles | 0.02 | 0.99 | 1900 | 880 |
| | Lime mortar | 0.01 | 0.7 | 1800 | 1100 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | EPS | 0.15 | 0.041 | 20 | 1260 |
| | Vapor insulation | 0.001 | 0.17 | 600 | 1050 |
| | Fir plates | 0.02 | 0.13 | 600 | 1610 |
| | | | | | |
| | Layers of building element | Thickness (m) | Thermal transmittance (W.m$^{-2}$.K$^{-1}$) U | Solar heat gain coefficient SHGC | Visible transmittance VT |
| Windows | Low-E argon filled Dual pane glass | 0.028 | 1.48 | 0.685 | 0.79 |

## C. Drawings

The test models for the examined houses are created from their plans and sections. Each zone includes a volume created from the outside perimeter of a room (or significant space) or in the case of adjacent zones - the middle of the separating construction was taken instead of the outside perimeter. The plans were created from the documentation provided by the National institute of cultural heritage in Sofia, Bulgaria and the Ancient Plovdiv Institute. The provided documents are based on the on-site measurements made by arch. Christo Peev in the 1950s and some of his drawings which can be found in his book “Plovdiv houses during the Revival epoch” (Peev, 1960). The sharing of personal copies of the Institute’s documents is not allowed so the following plans were created for the purposes of this research.

- House Hindlyan

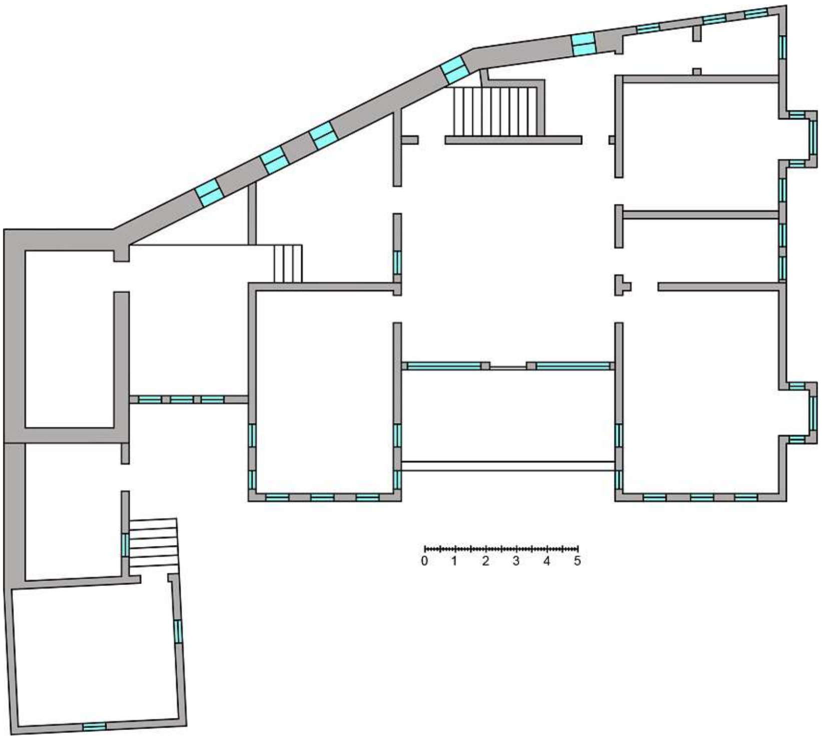

*Figure 99 House Hindyan – ground floor plan*

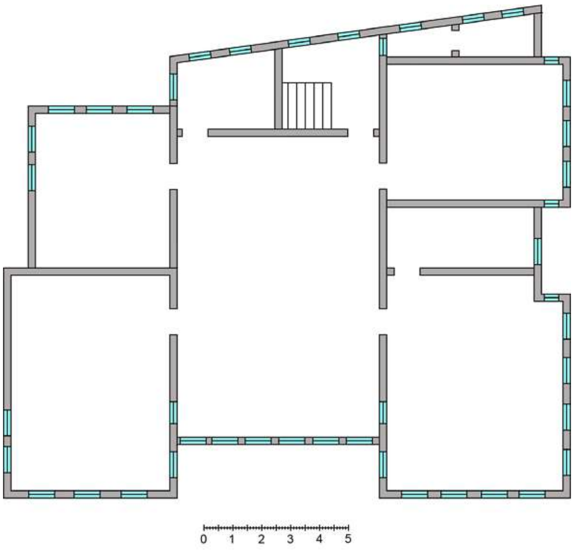

*Figure 100 House Hindyan – first floor plan*

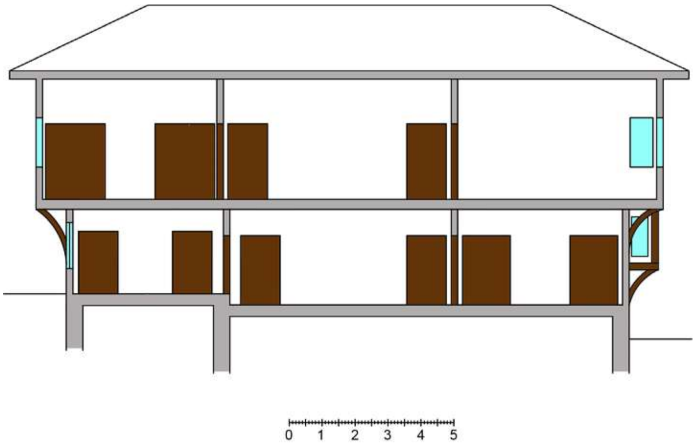

*Figure 101 House Hindyan – section*

- House of Dr. Stoyan Chomakov

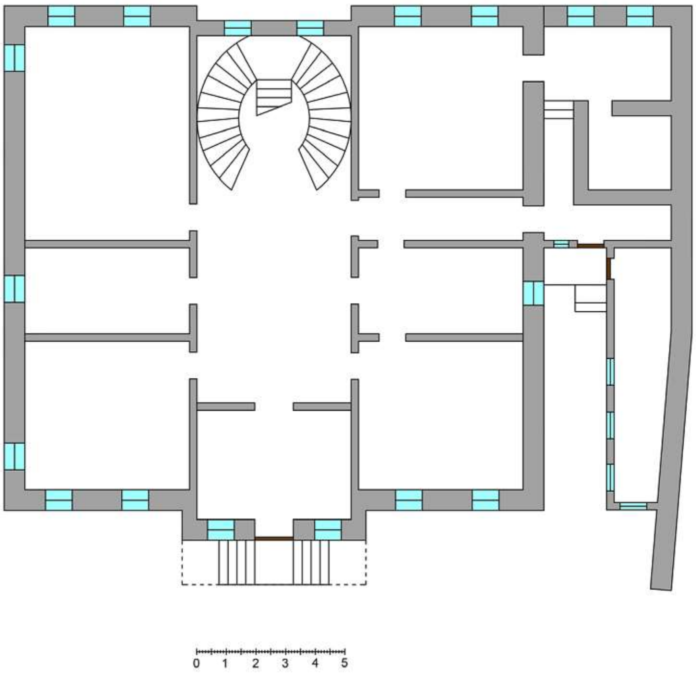

*Figure 102 House of Dr. Stoyan Chomakov – ground floor plan*

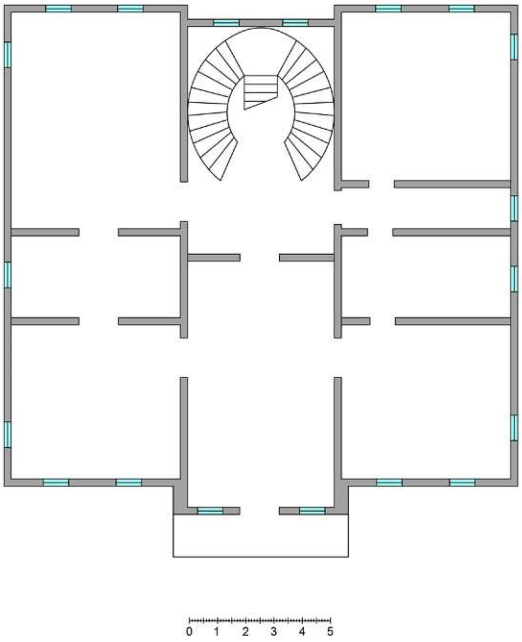

*Figure 103 House of Dr. Stoyan Chomakov – first floor plan*

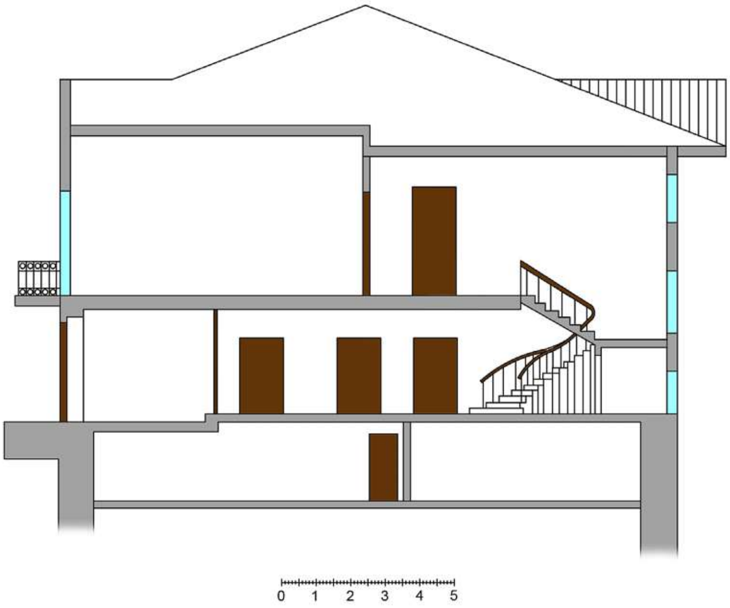

*Figure 104 House of Dr. Stoyan Chomakov – section*

- House Lamartine

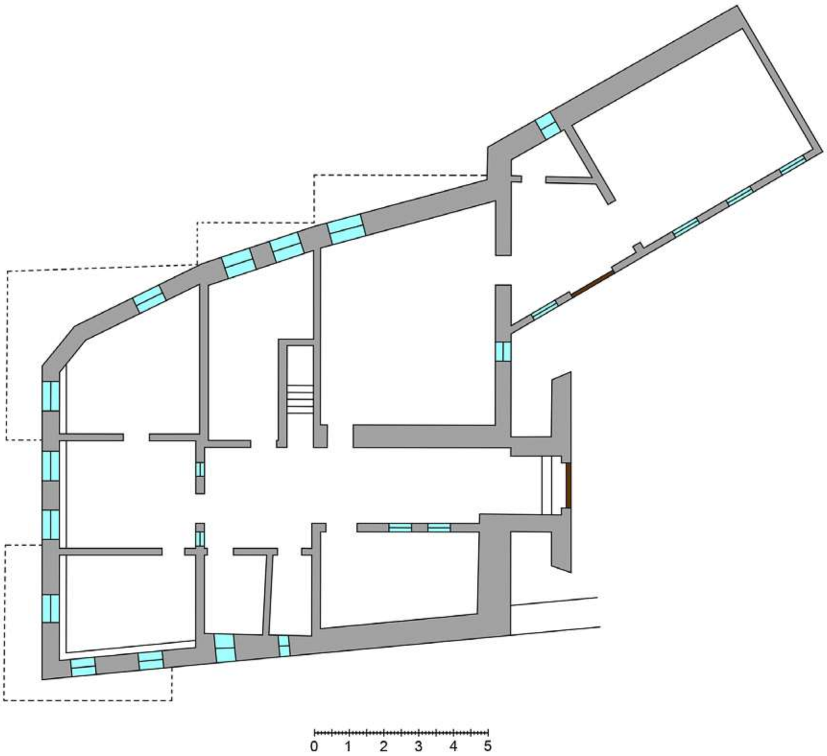

*Figure 105 Lamartine house – ground floor plan*

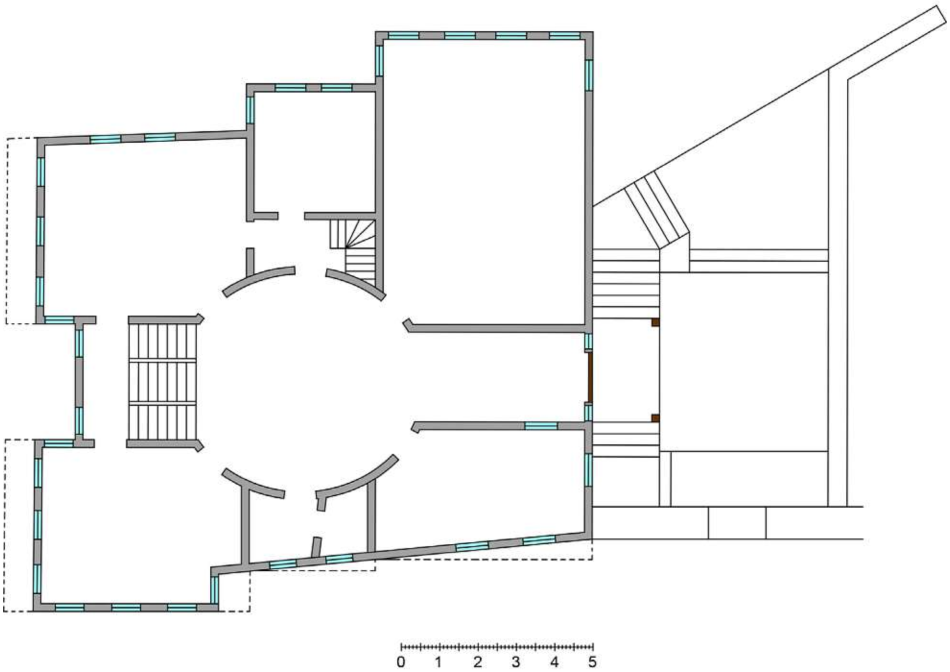

*Figure 106 Lamartine house – first floor plan*

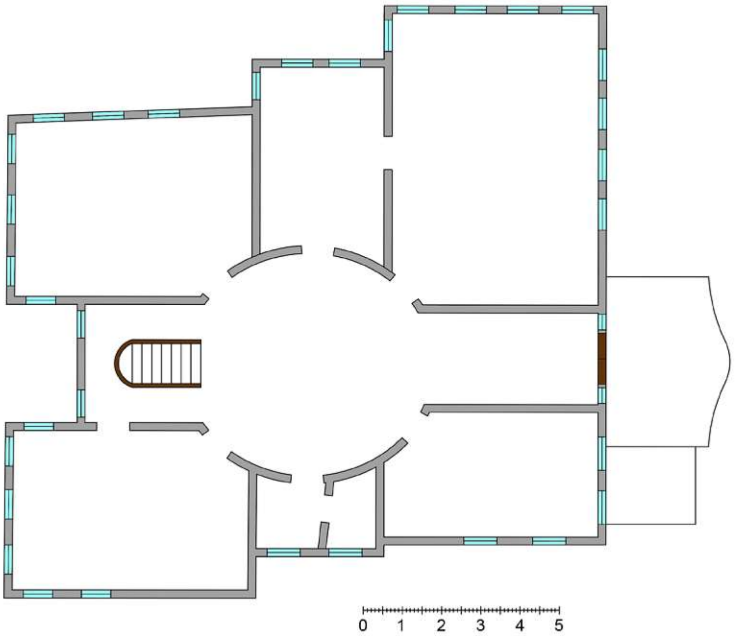

*Figure 107 Lamartine house – second floor plan*

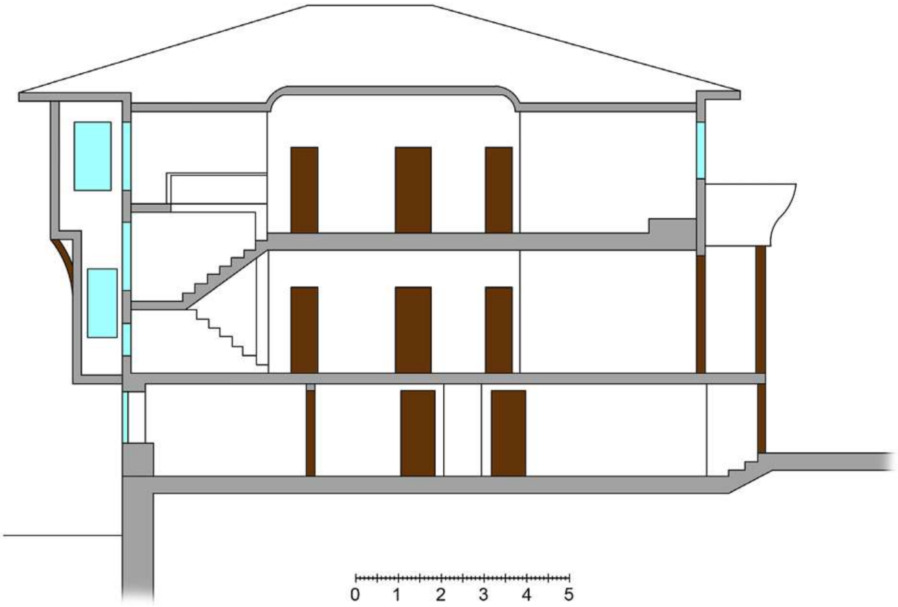

*Figure 108 Lamartine house - section*

- House of Dimitar Georgiadi

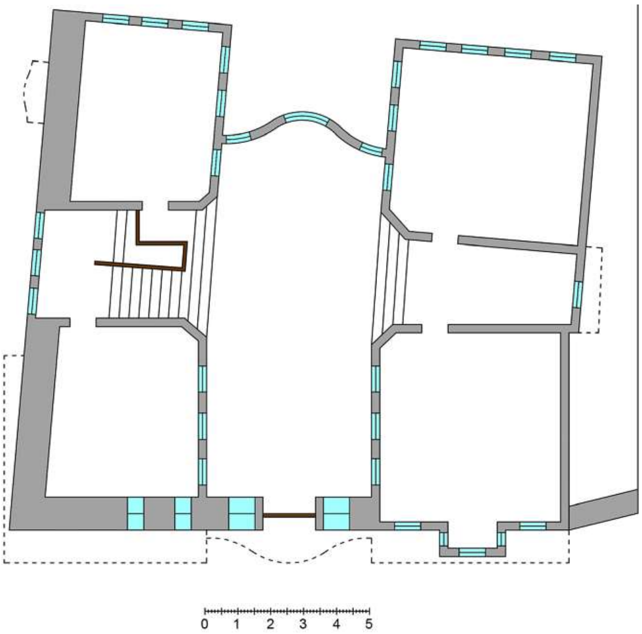

*Figure 109 House of Dimitar Georgiadi – ground floor plan*

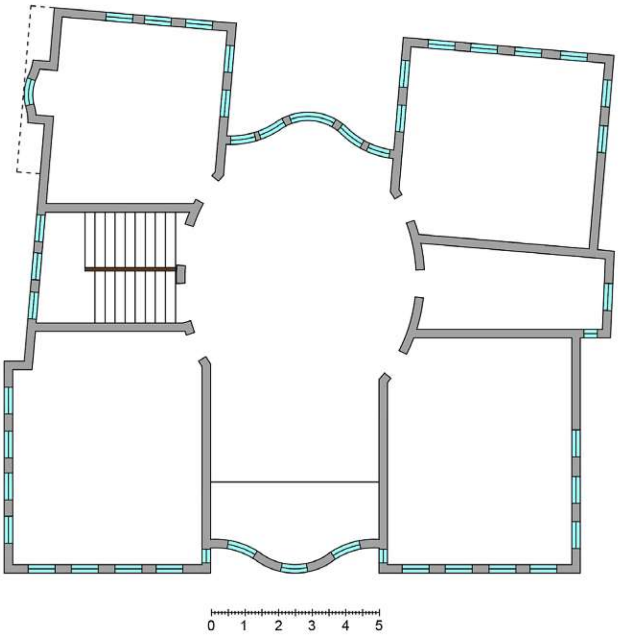

*Figure 110 House of Dimitar Georgiadi – first floor plan*

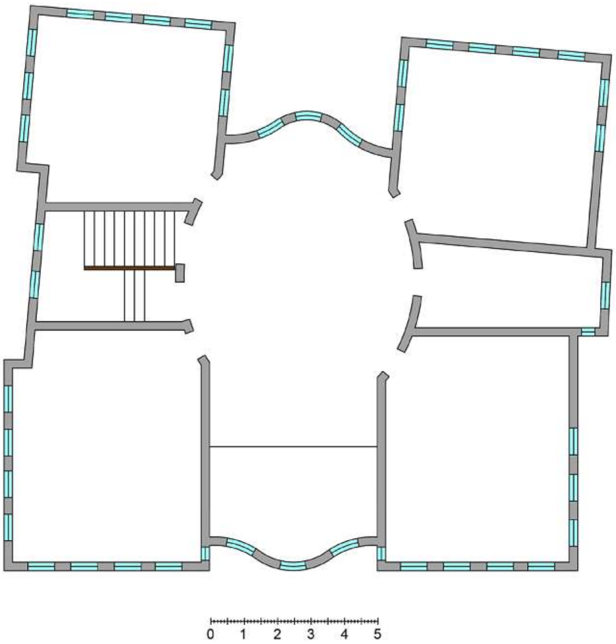

*Figure 111 House of Dimitar Georgiadi – second floor plan*

*Figure 112 House of Dimitar Georgiadi - section*

- Kuyumdzieva house

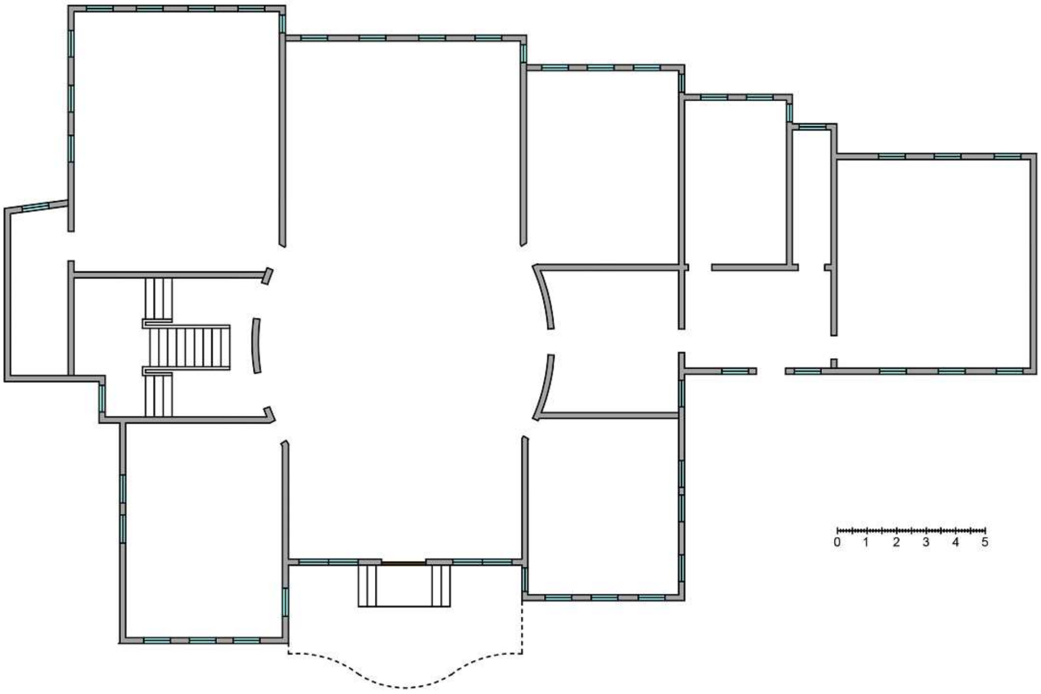

*Figure 113 Kuyumdzieva house – ground floor plan*

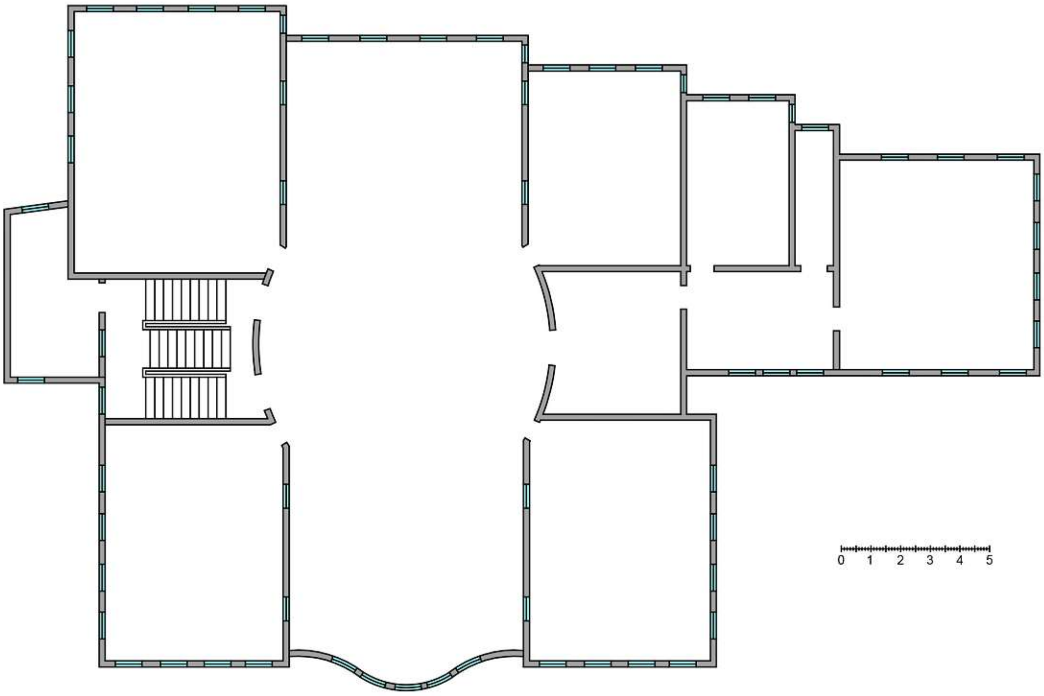

*Figure 114 Kuyumdzieva house – first floor plan*

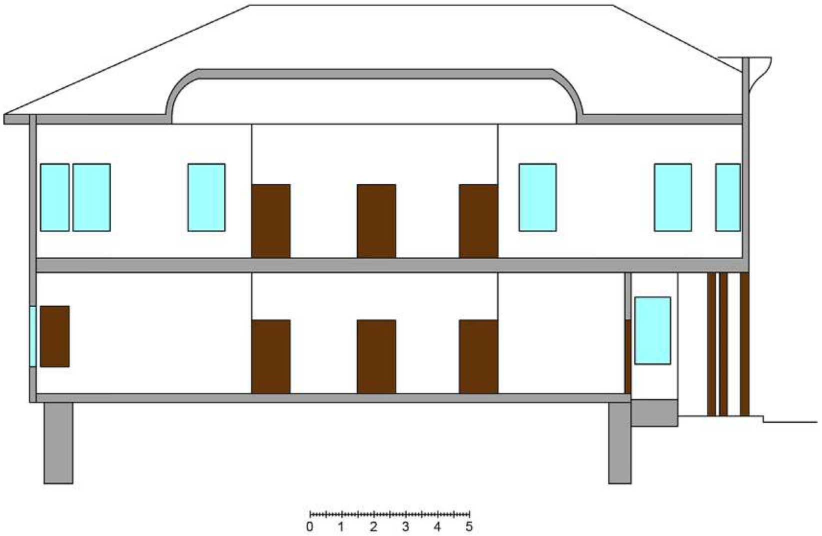

*Figure 115 Kuyumdzieva house - section*

# D. Additional climate data

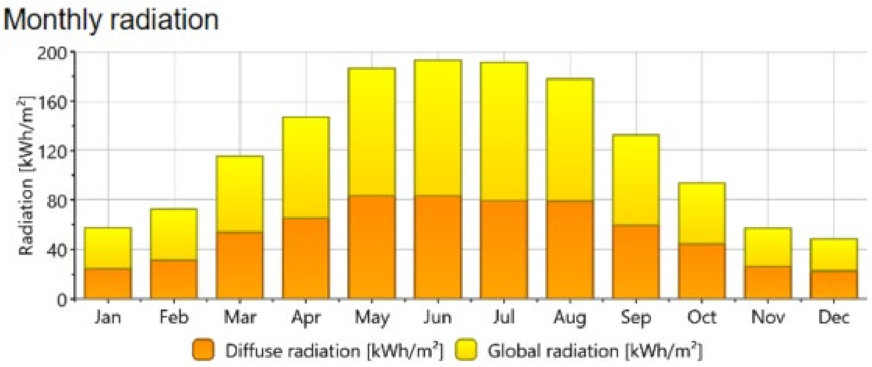

*Figure 116 Monthly solar radiation for Plovdiv (source:Meteonorm)*

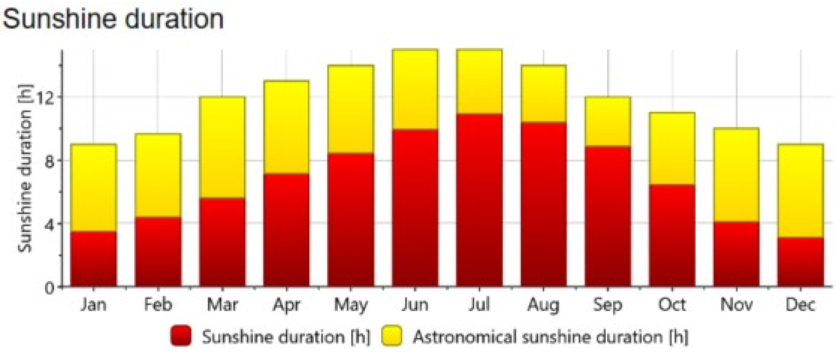

*Figure 117 Monthly values of sunshine duration of Plovdiv (source:Meteonorm)*

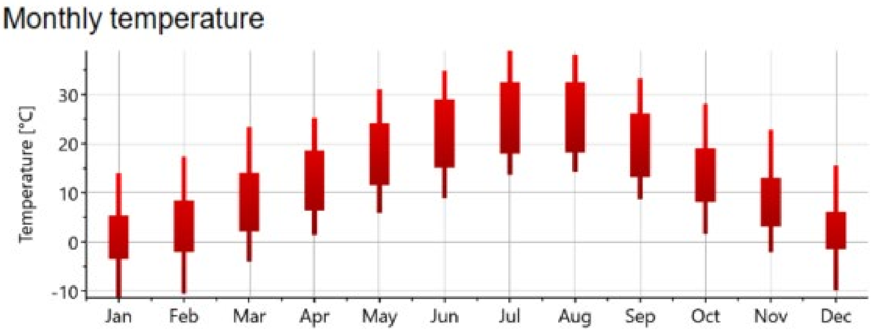

*Figure 118 Monthly temperature values of Plovdiv (source:Meteonorm)*

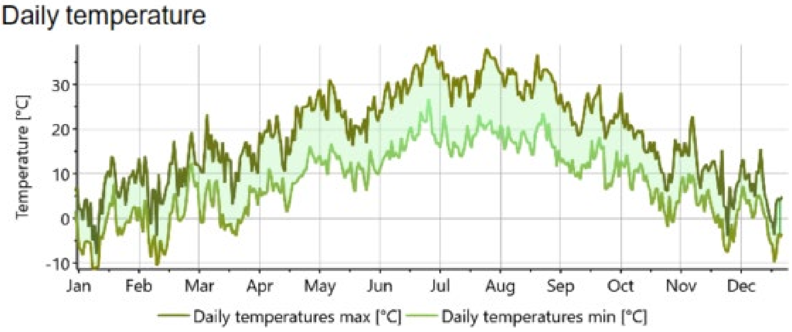

*Figure 119 Daily temperature values of Plovdiv (source:Meteonorm)*

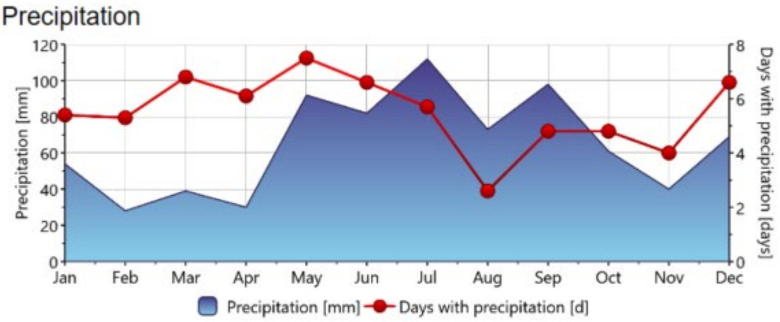

*Figure 120 Daily precipitation values of Plovdiv (source:Meteonorm)*

*Table 25 Monthly and average annual weather data for Plovdiv (source:Meteonorm)*

| | Global radiation (kWh.m$^{-2}$) | Diffuse radiation (kWh.m$^{-2}$) | Direct radiation (kWh.m$^{-2}$) | Temperature (ºC) | Dew point temperature (ºC) | Wind speed (m.s$^{-1}$) |
|---|---|---|---|---|---|---|
| January | 57 | 24 | 99 | 0.9 | -2.5 | 2.9 |
| February | 73 | 31 | 96 | 3.4 | -1.2 | 3.1 |
| March | 115 | 54 | 116 | 8.1 | 1.7 | 3.4 |
| April | 147 | 66 | 133 | 12.7 | 5.8 | 3.2 |
| May | 187 | 83 | 158 | 17.7 | 10.8 | 3 |
| June | 193 | 83 | 165 | 21.9 | 14 | 3.1 |
| July | 191 | 79 | 167 | 24.5 | 14.3 | 3.2 |
| August | 178 | 79 | 155 | 24.5 | 13.9 | 2.9 |
| September | 133 | 60 | 126 | 19.5 | 10.9 | 2.9 |
| October | 94 | 44 | 106 | 13.3 | 8.1 | 2.4 |
| November | 57 | 26 | 82 | 8.1 | 4.2 | 2.4 |
| December | 48 | 22 | 79 | 2.4 | -0.9 | 2.7 |
| Annual | 1470 | 653 | 1481 | 13.1 | 6.6 | 2.9 |