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Evaluation of the Thermal Comfort in Traditional Houses [Bukovina]

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Abstract

In an era in which we focus on making buildings as energy efficient as possible, vernacular architecture is a topic to be considered.

Traditional houses from Bukovina are solid examples of vernacular architecture. Some dating back over a century are still functional. This type of constructions harness the knowledge and experience of many generations. Being built with consideration of the surroundings, local materials, and simple technologies, they can be regarded as an inspiration for an environmentally conscious design.

This research focuses on the thermal behavior of traditional single-family units from Bukovina, in the Northeastern part of Romania.

To investigate the thermal response under different conditions, four different houses were chosen as case studies and a series of numeric thermal simulations were performed.

Five different scenarios were simulated: the first one assessed the thermal response of the houses in their current state, while the following four scenarios assessed the thermal performance of the buildings while their envelope is progressively improved. The tracked performance indicators were heating demand, transmission losses, and losses due to air change, solar gains and internal gains. The need for cooling demand was also investigated, in order to assess the presence of overheating during the summer months.

In the last two scenarios, a building renovation scenario was simulated, in which the thermal performance of the building envelope was improved by adding a layer of thermal insulation of sheep wool and polystyrene, respectively. The performance of the two materials was assessed through simulations and a Life Cycle Analysis. The results show that the sheep wool insulation has a thermal performance comparable to polystyrene, but displays many advantages in environmental performance.

In the state they are currently in, traditional houses from Bukovina do not meet the requirements for energy efficiency. However, this study suggests that by implementing simple measures, the shortcomings could be remedied. Renovating the houses, by improving the thermal resistance of the exterior building elements and providing air tightness and waterproofing would ensure that the traditional houses meet current thermal performance standards.

Keywords: Dynamic simulation; Thermal comfort; Energy efficiency; Vernacular architecture.

Kurzfassung

In den im Moment stattfindendene Bemühungen, Gebäude so energieeffizient wir möglich zu gestalten, kann das Analysieren von vernakulärer Archiktektur einen Erkenntnisgewinn bringen. Die traditionellen Häuser in der Region Bukovina sind ein gutes Beispiel für vernakuläre Architektur, die auf den lokal verfügbaren Materialien fusst. Einige dieser Bauten sind über hundert Jahre alt und weitestgehend unverändert noch funktionell und in Gebrauch. Die Entstehung der Bauwerke basiert auf dem Wissen, dass sich hinsichtlich des Bauens über viele Generationen bei der lokalen Bevölkerung gesammelt hat. Wichite Einflussparameter waren die Umgebungsbedingungen, die verfügbaren Baustoffe und die nach Möglichkeit möglichst unkomplizierte Herstellung der Bauwerke. Zusätzlich können diese Gebäude als Beispiele für sehr umweltbewusstes Design betrachtet werden.

Diese Master-Arbeit betrachtet die thermische Performance von traditionellen Einfamilienhäusern in der Region Bukovina im Nortosten Rumäniens. Um das thermische Verhalten solcher Bauwerke untersuchen zu können wurden zunächst vier verschiedene Gebäude als Case-Study-Bauwerke ausgewählt und mit Hilfe von numerischer thermischer Gebäudesimulation untersucht. Dabei wurden fünf verschiedene Szenarien betrachtet. Diese Szenarieren sind ein Basisfall, welcher den gegenwärtigen Zustand der Bauten berücksichtigt, sowie vier verschiedene Optimierungsszenarien, welche die thermische Performance der Bauwerke verbessern sollen.

Zur Bewertung der Performance der Gebäude unter den verschiedenen Szenarien wurden die folgenden Leistungsindikatoren herangezogen: Heizlast, Transmissionswärmeverluste, Lüftung infolge von Infiltrationseffekten, solare Wärmegewinne, interne Gewinne, sowie Kühlbedarf bzw. Risiko für sommerliche Überwärmung.

In zwei der Szenarien wurde eine Gebäuderenovierung unter Einsatz von Wärmedämmstoffen emuliert. Dabei wurde die Gebäudehülle in einem Fall mit Dämmung aus Schafwolle, in einem anderen Fall mit einer EPS-Dämmung versehen.

Zusätzlich zu den bereits genannten thermischen Kennwerten wurde eine Lebenszyklusanalyse für diese beiden Fälle durchgeführt. Die Dämmung aus Schafwolle zeigt bei einer vergleichbaren thermischen Performance eine Reihe von Vorteilen gegenüber dem synthetischen Dämmstoff EPS.

Der aktuelle Zustand der betrachteten, traditionellen bukowinischen Gebäude ist nach dem Maßstab heutiger Anforderungen als energetisch unzureichend zu bezeichnen. Allerdings zeigen die Ergebnisse dieser Arbeit, dass mit vergleichsweise einfachen Maßnahmen, dieser Zustand verbessert werden kann. Bei einer entsprechenden hochbautechnischen Ausgestaltung dieser thermischen Sanierungen, im Speziellen unter Berücksichtigung einer erhöhten Dichtigkeit der Gebäudehülle, lassen sich durchaus gute thermische Performance-Werte erzielen.

Acknowledgement

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Dedicated to my parents

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1. Introduction

Bukovina *"by its folk tradition is a true open-air museum, which still preserves, in most of the rural areas, living examples of the originality and perpetuity of the building techniques."* (Chitonu 2012)

Over time, in urban areas, the architectural landscape has known many different styles and currents. However, the traditional rural houses were built and rebuilt, each preserving the specificity of the area in terms of local materials and architectural style. The latter, being adapted to the relief and climate conditions, improved from one generation to another.

Out of concern for the future, each nation should adopt a prioritizing policy to protect and conserve its environment and natural resources, as nature is not a legacy from our ancestors but rather a loan form future generations to come. Reviving the folk tradition of Bukovina is a chance to learn once more how to live in an ecological manner by understanding and making use of nature's cycles.

If people were to revive the vernacular construction techniques that have been verified for centuries, that show durability by having passed the test of time, and apply the ecological principles, this would lead to a superior quality of life, backed up by the experience of past generations.

1.1. MOTIVATION

The Historical Region of Bukovina is located in Central Europe, with its territory currently being spread over the area near Suceava, Câmpulung Moldovenesc and Rădăuţi in Romania and Chernovtsy in Ukraine. The territory of the Romanian Bukovina (also known as Southern Bukovina) is located on the north-eastern part of Romania, and it is part of the Suceava County. In the Romanian culture, Bukovina is considered one of the hearts of ancient civilization which developed and accumulated some of the oldest morph-structural types of folk architecture, many of which still exist today.

The geography of the area, strongly forested, resulted in people opting for mainly wooden constructions. The construction system of the houses combines a traditional wooden baring structure overplayed with a mixture of clay and straw on a wattle support. The clay used in this type of construction falls in the category of light clays, with no structural role, but closing and insulating role. (Maftei et al. 2011)

Traditional construction techniques, making use of wood, are still present in the local household. Continuing using wood, and using new building materials in harmony with the traditional ones presents itself as an effective solution in terms of aesthetics, economics and technology.

In a rapidly industrializing global market, where the products go increasingly through mass production, resulting in loss of quality in favor to high quantity and low price, there is great potential in traditional trades and crafts that are slowly disappearing. Using local materials and local building techniques is both an important pole of Romanian culture and heritage and an important European development potential on a market eager for exoticism and uniqueness. (Romanian Order of Architects, 2011)

If we exclude preconceptions and demands imposed by contemporary aesthetics, drawbacks of this type of construction are minor. Whereas advantages are numerous, such as sustainability, reduced CO_2 emissions, reduced costs, less technical appliances, improved health.

Increasing living standards in Romania has as a consequence new requisites. One of these requisites is to improve the quality of life in rural areas.

Therefore, the goal of this study is to assess the thermal performance of the traditional local architecture in order to act as an incentive for the local population of Bukovina not to disregard vernacular construction means and methods. If reconsidered, the latter could become a state of the art ecological solution, bringing a general improvement of the quality of life of local inhabitants.

*"If the principles of sustainability and sustainable development can be transmitted by tradition, then, their implementation will be faster, and the future generations will learn to preserve their history and at the same time enjoy a healthy and unpolluted environment."(*Chitonu 2012)

1.2. SCIENTIFIC BACKGROUND

The evolution and modernization of society lead to great advances in technology, but also brought a series of problems, such as high energy consumption and pollution, that put our planet and health condition at risk. Therefore, passive buildings made of ecological materials have been a focus of many studies over the past decade. To support this idea, the study performed by Chitonu (2012), on the potential of traditional Romanian habitat to develop sustainable architecture, shows how it is by focusing in the wrong direction that we reached this state of economic crisis, and how it is important to focus our attention towards protecting and improving the rural habitat.

The study of traditional architecture from Diyarbakir, Turkey relegates the importance of energy-efficient and climate-conscious buildings, that are appropriate for the environment. Although not militating for a return to the old constructive techniques, Sozen and Gedik (2007) conclude that the guidelines used to create the old dwellings are timeless, and people should adopt them again, considering new technological advances, techniques, and materials.

The study on the thermal behavior of historical dwellings in France has a remarkable outcome. Although initially appreciated only for their local architectural, patrimonial, aesthetic and historic interest, the historical buildings actually proved to be less energy consuming than the modern ones. Having a strong correlation between the indoor and outdoor environment, showing that *"these historical dwellings are interactive systems, with bioclimatic properties more complex than the modern dwelling, with similar energy performance"* (Cantin et al. 2010). However, it is recommended that the restoration project is done carefully, for the lifespan of historical dwellings could be reduced because of inappropriate retrofitting, which can modify their thermal balance.

The systematic approach to thermal adaptation of detached single family buildings in Kosovo (Islami 2007) study is performed on houses with a constructive system made of masonry blocks, which have no thermal insulation. This lead to temperatures inside being equal to those outside at night, during the cold season, when the heating was turned off. The results reveal the fact that properly insulating a dwelling does not only present benefits in the cold season, by providing a higher thermal comfort for a lower energy demand, but also during the hot and dry periods of the summer, protecting the dwelling from overheating.

The thermal assessment of the vernacular houses on the Israeli coastal plan, conducted by Aleksandrowicz (2012), showed that the Israeli houses in that region do not perform well thermally. Although it was expected for vernacular architecture to embody valuable solutions for maintaining desirable indoor conditions, the conclusion was that the spatial scheme of the analyzed type of house *"had much more to do with formal and cultural conventions than with its sheer thermal performance."(*Aleksandrowicz 2012)

Considering prior research, investigating the feasibility of thermally adapting old traditional houses from the region of Bukovina could prove to be a valuable incentive for people to continue using them, thus saving energy, protecting the environment, improving their living standard and keeping the architectural landscape authentic.

1.2. HISTORICAL BACKGROUND

Bukovina, also known as "the upper land" of Moldova, was until the year 1775 the historical province of Romania with the most conflicted history, with many inter-ethnical interferences, that have left their mark on the particularities of the area.

The name "Bukovina" stems from the German term "Buchenland", which means "The land of beech trees". It was given by the Habsburg Empire, to which the area belonged for 144 years, between the years 1775 and 1918. In 1940 it was divided into two areas: North Bukovina, which today belongs to Ukraine, and South Bukovina, currently part of Romania.

Since ancient times, Southern Bukovina represented the permanently stable connecting axis of Transylvania with Moldavia. This axis represented the "gate" for people passing from one mountainside to the other side, for migrations towards Transylvania and Pannonia, for the medieval and modern armies in the fights and later in wars, but also for population colonization and migrations or trade. (Dinca 2009)

"Magical land, full of legends, Bukovina was molded in a geography full of grandeur and solemnity, which unfolds as a huge natural amphitheater with steps descending from sunset to sunrise. Parallel rows of ridges (obcini) with towering forests of fir, beech and spruce, endowed with pastures and

*meadows which maintain their green color until snow falls (…) follow one another like frozen waves far into horizons."(*Ielenicz 2006)

Bukovina is an area with a rich cultural landscape, where charm and resources are inexhaustible. It includes historically rich cultural heritage, with many elements of international value (such as the monasteries, which are on the UNESCO world heritage list).

The study area is a territory between rural areas and countryside. It is rural due to the agricultural activities of the local farmers, and natural because the landscape represents a particularly attractive background, corresponding to the image of "nature" and "relaxation". The territory provides a number of remarkable sights.

Figure 1 Bukovina landscape (photo archive of the author)

Figure 2 Map of Bukovina Region (O.A.R. 2011)

1.3.1 The traditional habitation

In ancient times indigenous believed there was a very strong sense of solidarity, namely that the single cannot be understood without the whole. The household was shaped over time, based on the needs of people and local natural conditions. The household ensemble is positioned facing the street, but taking up only one part of the side of the parcel, thus facilitating the transition to the backyard. The enclosures respect the same functional reasons.

The interior has a specificity and a critical role in the life of residents, providing a sheltered space. It hosts various household activities and special events. In the traditional household from Bukovina, although each element performs a different role, the whole is achieved by using a common language that provides the whole assembly with unity.

The parcel is occupied according to two functional principles.

The first one is the semi-enclosure principle, that closes the homestead on three sides and which was preserved regardless of the position of the house. The street side is open towards the community through the gate element that has delimitation as a practical role and as a symbolic role it has the representation of the inhabiting family. An interesting feature is the covered, yet open space that links built objects, protects and also facilitates the transition from one space to another. Also, the roof, by means of its texture and shape, gives unity to the whole built ensemble.

The second kind of occupying the plot, also called the “polish” type of household, is characterized by aligning the two slopes to the street (and not by south orientation), having a more urban feel. This typology is most common in villages where there was a Polish majority of inhabitants. The courtyard, although involving the same functions, doesn’t enclose the three sides, and the gate plays a secondary role. However, households do not form a continuous front because the lot is halved, with direct access from the street.

Vernacular architecture from Bukovina is defined by harmony, in ideal agreement between volume, material and technology. These elements are what makes up the scale and character of the traditional village. They must be understood in their entirety to be retrieved. It is a human-scale architecture of great sobriety and sensitive elegance highlighted by a fine sense of proportions. These proportions come from a knowledge of the strengths and limitations of the construction material (wood) and from respect of traditions inherited for centuries, in relation to regional conditions (genius loci).

The house is the main element of the household, and it is facing the sun – the main façade is south oriented, out of both practical reasons but also symbolic ones.

Regarding its planimetry, the traditional house has had a long evolution. In the beginning it assumed a one-room building, known in the specialty literature as the Single-Cell or Monocellular house type. Its widespread, and the fact that it was easy to use, made the Single-Cell house to be the most popular type throughout the Feudal period in to modern times and even in the contemporary period. The Single-Cell hut has always been easy to build. Its constructive system was the simplest, even in times of empirical technology. It consisted of a single space with maximum concentration of the family life, which withheld all the family members, all the furniture and possessions. In this space, around the archaic hearth, is where all the annual ceremonials of the family took place. In this room, the hearth had a central function of the human habitat. In relation to it, not only was the entire living space organized, but also the schedule of the mythical traditional events.

In the Romanian tradition, similar to that of other nations, when building a house, the people first picked the spot for the hearth. There they stuck a cleat that served as the "axis mundi", around which the house was then built. The archaic hearth was the place for the production and maintenance of fire, and it was designed as a circular or rectangular enclosure bounded by some river stones. Later it took the shape of a heating oven and the place for food preparation, and in some cases it also served as a shrine, on which people used to burn ceremonial offerings.

The Single-Cell houses still impress with the balance of their proportions, the simple yet elegant décor, played by the contrast between the brown patina of the wall beams and the white framings around windows and doors.

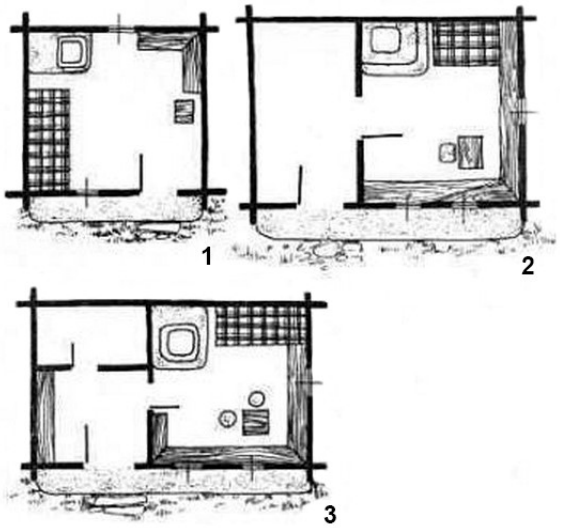
In the classical stage of evolution of the vernacular houses (the 15th century), new, more advanced functional types appear, which do not have correspondences in previous eras.

Starting with the Princely era, the old prototype of Single-Cell housing becomes unsatisfactory and not corresponding to the new requirements of comfort or the new economic structures. The house layout naturally tended to progress towards more comfort. From the old one-room layout evolves the house with an unheated hallway and a living room. Unlike in other parts of the country, as well as from all across the Carpathians, in Bukovina the house layout underwent a development based on the relation between the rooms and the hallway. The planimetry is carried out either symmetrically or asymmetrically in relation to this area, and sometimes a pantry (a storage space at the back of the house) is added. From this moment on, there is a functional separation of the interior from exterior spaces, through the creation of a destined space for housing: the heating chamber. In the new housing area, the hallway takes on some specific functions: in addition to being a space both connecting and isolating the living room and the exterior, it also becomes the place where the attic is accessed from, as well as a storage space for food and household utensils.

The prior direct access from outside into the living room had as a result a large amount of heat loss, and this problem was now being solved with the addition of the hallway as a transition space. The ingress was made from the porch through the hallway, leaving the function of hearth to the room in which the family lived. This meant real progress in terms of hygienic conditions.

At the beginning of the 17th century, a new house layout is developed: the symmetrical house plan, with a hallway and one room on each side. One of the rooms was destined for permanent living, while the other one was a presentation space, often called "the clean room", where valuable objects were kept and was used only on special occasions. The 19th century represents the crest of folk architecture. Houses with a more developed planimetry begin to rise, some even having four rooms and a corridor set around the building. The roof is now supported by a larger number of beams, thus the pillars are gaining decorative valences.

Specific to Bukovina is the German cultural influence, which took place in this area at the middle of the 18th century. This aspect lead to radical changes in the way the villages look here, as compared to the rest of the country. Here, without abandoning the local cultural and architectural background, a visible planimetric expansion and improvement of interior configuration takes place.



1 Monocellular house
2 House with unheated hallway and one room
3 House with unheated hallway, one room and storage room

Figure 3 Traditional House Layouts: (Camilar 2011)

The German influence manifested itself in many aspects: from the constructive technique of four-faced carved beams, lapel joints at the corners, massive barns and multipurpose enclosures, to vertical development through attic rooms and the emergence of "pinion" houses. (Camilar 2011)

The walls of this type of houses are made of round fir wood beams, and the windows are small penetrations in the walls. On the northern side, with access from the entrance hall or outside porch, at times there is also another room used for storage – the "sopra".

The openings are relatively small and are amplified to the exterior by framings that were plastered (with a combination of clay, straw and dung) and then whitewashed. This is often to be seen in Bukovina, as it is one of the architectural characteristics of the area.

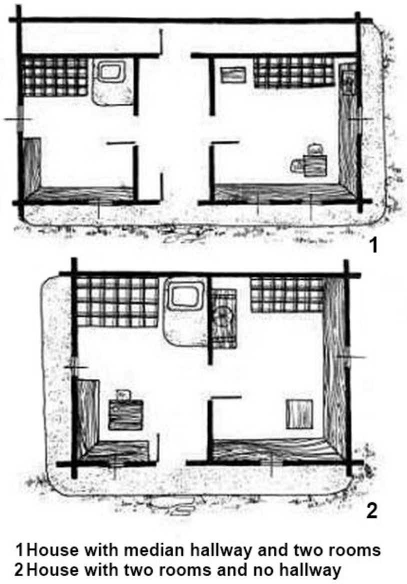


Figure 4 Traditional House Layouts: (Camilar 2011)

The porch is one of the most important elements of the house architecture and is representative for the traditional architecture here. It is an intermediate built space, between nature, man and the community. It is an element that reflects a way of living and represents the joy of communication, specific to the traditional society, but it also serves as protection against weathering. It is developed on either one, two or three sides of the house. The initial porches consisted of stones and a clay filler, having the same height as the foundation. In the 19th century, the materials are replaced with wood planks. Shortly after, the porch evolves into being fully enclosed with wood planks, and it gets the name of "gangway". When the porch level is higher, due to the foundation being high as a result of the adaptation to the natural terrain slope, wood or stone steps were provided at the entrance in order to access the house. The porch was carried out on one or more sides of the house. By means of its neutrality, it is a true filter that separates the house from the exterior environment. It has great utility and importance in the traditional architecture. This is where most of the family activities took place. This is where people dined during summer, slept and carried out household activities.

The shape of the roof is also determined by the local climate (abundant snow or rainfall). It has four slopes that are covered with shingle. The ratio of the height of the roof and that of the walls is what generates the harmony of the house. The capacious attic serves as food storage. The traditional house does not have a chimney, but the smoke is released directly into the attic and from there it goes outside through a specific type of smoke discharge outlets named "fumarite" (Romanian term), also popularly named "ox eyes". The smoke has the role of preserving the edibles stored in the attic while providing protection to the wood from which it is built. The shingle, with its flexibility and ability to preserve the certain shape it was given, creates rounded edges between the slopes and the ventilation outlets. On the North side of the roof, the slope is often extended, offering better outside protection and extra storage space. In some cases, it is enclosed.

The decorations are symbolic. For instance the crested larks, and the stylized images of birds, have a beneficial role in popular belief.

Figure 6 Traditional house with slanted roof (Photo archive)

Figure 5 Detail of shingle and smoke outlets (Photo archive)

Religion and church play an important role within the community, providing it with drive and unity. Numerous Christian holidays cultivated traditions that have been preserved for hundreds of years. At the same time, in recent years a strong phenomenon can be noticed, of labor migration of young people, age 16 to 45, to developed countries of the European Union, while the elderly and children remain in the villages. People in the area are considered hardworking, straightforward and complex-free, taking pride in their place of origin.

Traditional crafts and trades are extremely important elements of the cultural landscape of Bukovina. They determine how the houses and everyday objects are built. Crafts can become tourist attractions precisely because they are still part of the everyday life, as opposed to the situation in other countries where they are just staged.

1.3.2 Transformations and mutations

The cultural landscape is constantly changing and in the last 50 years, the Romanian village has undergone several transformations.

A transformation that has imposed major changes was produced in the communist period, when a certain type of house project was imposed. This brought changes in terms of the image of the house, the volumetric appearance, façade treatment, and height (the new houses had a ground floor and a half-floor). However, these modifications did not also bring the modernization of living conditions and lifestyle.

The transformations and mutations of the village occurred at different scales, from urban planning to changes of the construction techniques and materials.

Today there are two main factors that determine the transformation of the traditional village in terms of image: the general lifestyle changes and the modification of the core structure of the village from residential and agricultural to tourism.

Changes to the overall image of the village come from small-scale interventions. The strong individuality feeling and the use of new shapes and materials resulted in a total confusion in the general perception. This attitude of doing whatever one pleases or sees fit leads to losing local cohesion on many different levels.

The fact that the craftsmanship lost the importance it used to have in the traditional culture has become obvious. There are new architectural elements that have emerged, that are considered to be traditional, although completely different than the vernacular models. Traditional gates and wells are reinterpreted by craftsmen in a way that is contrary to the spirit of the place, using many different styles and decorations. People add elements that are not in fact related to local traditions, and materials and building elements are used contrary to the structural logic encountered in the traditional constructions.

Some of the houses were modified in a surprising way. The roof shingle, a traditional characteristic element for the Bukovina region, was replaced with iron plates. Also a common thing is the use of non-natural materials in order to cover the old wood frame of the houses. The elements that make up the ensemble image of the house, such as the openings and the porch were heavily modified. The volume of the house has also suffered modifications, in order to expand the living area. The first and most common way is by closing the porch and transforming it into what is called a greenhouse. Houses are also vertically extended by often adding one, two or sometimes even three new storeys.

The newly built houses fully abandon the features of the traditional house. They differ from the traditional ones in scale, proportions, materials and color. Nowadays, specific to the architectural horizon of villages is the dialogue between traditional models and those carrying foreign influences. This dialogue is characterized by either distance or return to local tradition, but not always in the best manner. (Camilar 2011)

2. Objective

The architectural landscape of Bukovina has known dramatic changes over the past 50 years. Due to the change in requirements to meet comfort, people have abandoned the traditional houses in order to build new ones that are usually out of scale and making use of energy embedding materials.

As the local climate has not suffered any noticeable changes, the old constructions might be able to offer some thermal comfort, and with improvements it is assumed that the traditional houses could perform thermally well enough to be further used.

For the refurbishment of the traditional dwellings sometimes complex techniques and procedures are necessary, as well as higher costs or a longer execution time. But the final result is far superior to the new types of buildings that have recently populated the area. Traditional architecture developed for centuries to come in harmony with the natural environment. Even attempts to take over traditional features and modern interpretations are often condemned to failure. Thus it is recommendable to keep the local traditional built environment in place and functioning. The old houses are worth being put to use, and subsidies to motivate preserving the authentic elements should be offered.

Awareness needs to be raised amongst residents, authorities and investors and also professional training of specialists in this type of renovation is required.

The objective of this study is to assess the thermal performance of traditional houses from the Bukovina region, investigating how they perform under current conditions and how they would perform if the thermal performance of their envelope were improved. The results are meant to aid local people in their decision-making process, and establish to which extent using the old houses and reintegrating the vernacular architecture principles in future projects is feasible.

3. Approach

3.1. COLLECTION OF DATA

In order to assess the thermal performance of the traditional houses from the Bukovina region, four house examples were chosen, that differ in several aspects. The vernacular houses were measured and drawn in digital format with precise dimensions, and a photographic documentation was carried out. Crucial elements to the thermal analysis and detailed information on the construction layers were gathered. The parameters envisioned for the study are as follows:

Table 1 Information gathered

Location	Latitude, Longitude, Altitude
Size	Overall Dimensions
Number of Rooms	Heated and Unheated
Construction layers	Materials of walls, slabs and roofs
Floor plans	Light source types and positions
Photographic documentation	Façade and construction details

The simulations were carried out in five cases. The first case is a simulation of the houses under the currents state they are in. The second case is a simulation of the buildings that have gone through a weatherization process, but the windows are still the original ones. In the third case, the already weatherized houses get the old windows replaced with energy efficient ones. In the fourth and fifth cases, the building envelope U-values were improved by adding a layer of thermal insulation of sheep wool, respectively polystyrene.

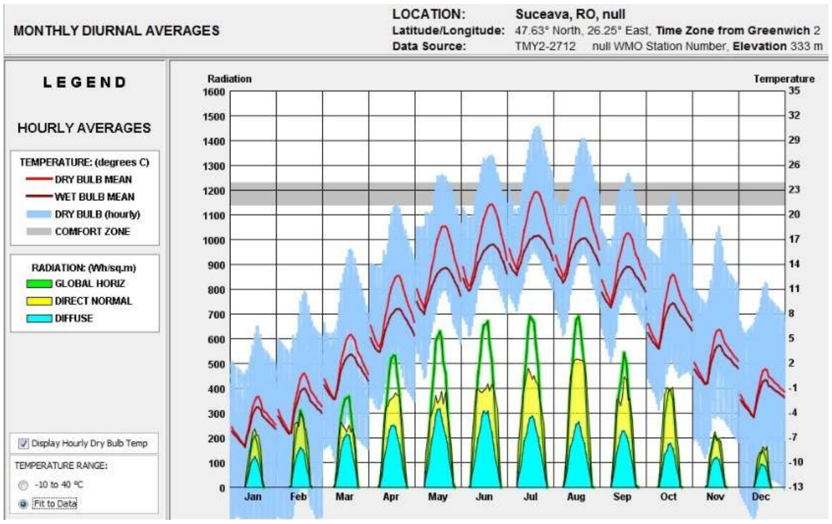
3.2. CLIMATIC DATA

The weather data was generated for Suceava county by means of the MeteoNorm climate software, as the local government was unable to provide detailed data on the subject. Suceava is located at 47,63 N and 26,25 E with an altitude of 332,86 m. The climate is classified as temperate continental with an Alpine tint, average temperatures ranging from 15 °C in July and 0 °C in February. Rainfall varies at around 800 mm and average pressure is situated at around 690 mm.(Engel et al. 2009)

The software Climate Consultant was used to visualize the content of the weather file.

For the simulations, the following parameters were generated:

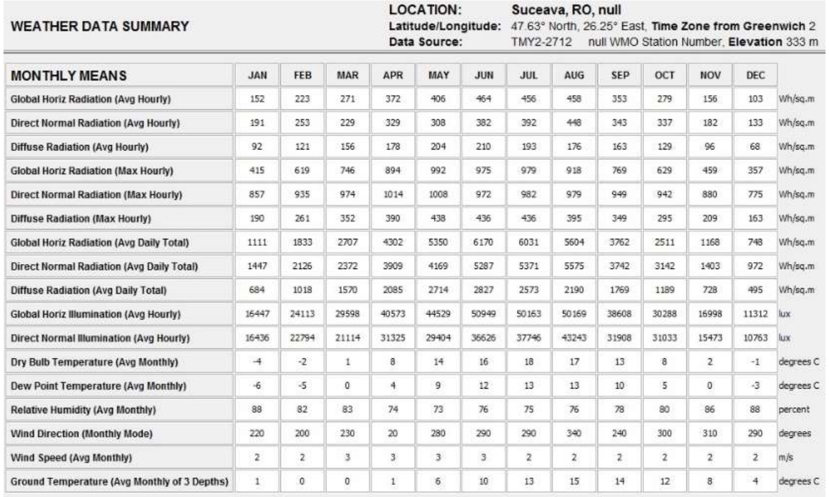
- Global solar radiation
- Diffuse solar radiation
- Cloud cover
- Dry bulb temperature
- Relative humidity
- Wind speed
- Wind direction



MONTHLY DIURNAL AVERAGES

LOCATION: **Suceava, RO, null**
Latitude/Longitude: 47.63° North, 26.25° East, **Time Zone from Greenwich** 2
Data Source: TMY2-2712 null WMO Station Number, **Elevation** 333 m

Figure 8 Weather Data Summary (Climate Consultant)



WEATHER DATA SUMMARY

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Latitude/Longitude: 47.63° North, 26.25° East, **Time Zone from Greenwich** 2
Data Source: TMY2-2712 null WMO Station Number, **Elevation** 333 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	152	223	271	372	406	464	456	458	353	279	156	103	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	191	253	229	329	308	382	392	448	343	337	182	133	Wh/sq.m
Diffuse Radiation (Avg Hourly)	92	121	156	178	204	210	193	176	163	129	96	68	Wh/sq.m
Global Horiz Radiation (Max Hourly)	415	619	746	894	992	975	979	918	769	629	459	357	Wh/sq.m
Direct Normal Radiation (Max Hourly)	857	935	974	1014	1008	972	982	979	949	942	880	775	Wh/sq.m
Diffuse Radiation (Max Hourly)	190	261	352	390	438	436	436	395	349	295	209	163	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	1111	1833	2707	4302	5350	6170	6031	5604	3762	2511	1168	748	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	1447	2126	2372	3909	4169	5287	5371	5575	3742	3142	1403	972	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	684	1018	1570	2085	2714	2827	2573	2190	1769	1189	728	495	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	16447	24113	29598	40573	44529	50949	50163	50169	38608	30288	16998	11312	lux
Direct Normal Illumination (Avg Hourly)	16436	22794	21114	31325	29404	36626	37746	43243	31908	31033	15473	10763	lux
Dry Bulb Temperature (Avg Monthly)	-4	-2	1	8	14	16	18	17	13	8	2	-1	degrees C
Dew Point Temperature (Avg Monthly)	-6	-5	0	4	9	12	13	13	10	5	0	-3	degrees C
Relative Humidity (Avg Monthly)	88	82	83	74	73	76	75	76	78	80	86	88	percent
Wind Direction (Monthly Mode)	220	200	230	20	280	290	290	340	240	300	310	290	degrees
Wind Speed (Avg Monthly)	2	2	3	3	3	3	2	2	2	2	2	2	m/s
Ground Temperature (Avg Monthly of 3 Depths)	1	0	0	1	6	10	13	15	14	12	8	4	degrees C

Figure 7 Monthly diurnal averages (Climate Consultant)

3.3. CALCULATIONS FOR ENERGY METRICS

The influence heat transfer has on a building can be seen in Figure 9.

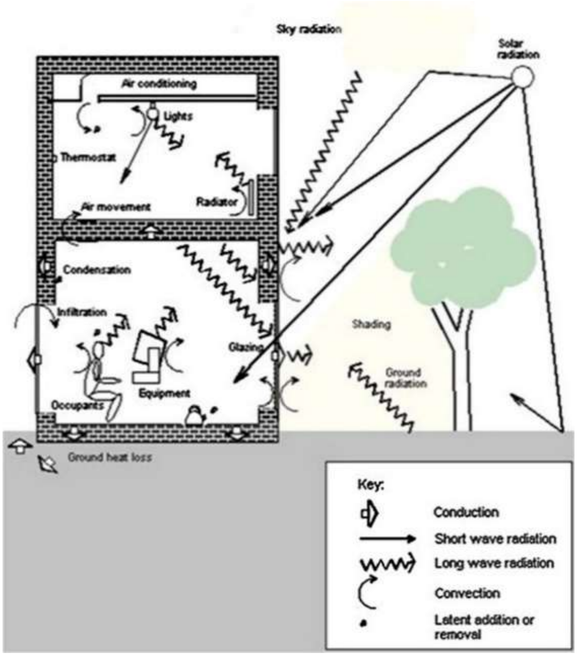

Figure 9 Schematic representation of heat transfer mechanisms in a building (EDSL TAS 2016)

Thermal transmittance | U-value [$W.m^{-2}.K^{-1}$]:

Thermal transmittance is the heat transfer rate per m^2 of a structure, divided by the temperature difference across the structure.

Formula: $U = \frac{1}{Rt} = \frac{1}{Rsi+Rt+Rse}$, where (Eq.1)

U is the thermal transmittance,

R_t is the sum of the thermal resistance coefficients of the different layers in the construction.

For windows the formula is: $U_w = \frac{Ag*Ug+Af*Uf+lg*\Psi g}{Ag+Af}$, where (Eq.2)

U_w is the thermal transmittance of the window,

A_g is the glass pane area,

U_g is the thermal transmittance of the glass,

A_f is the window frame area,

U_f is the thermal transmittance of the frame,

l is the perimeter glazing,

Ψ is the linear thermal resistance.

Heating load | Q_h [kWh]:

The heating load is the amount of energy required to heat up a room to a specific temperature.

Formula: $Q_h = (Q_T + Q_V) - \eta(Q_i + Q_s)$, where (Eq.3)

Q_h is the heating load,

Q_T is the transmission gain/loss,

Q_V is the ventilation gain/loss,

Q_i is the internal gain/loss,

Q_s is the solar gain and

η is the efficiency factor (dippending on weather the building is heavy or light constructed).

Heating demand | Q_d [$kWh.m^{-2}.a^{-1}$]:

The heating demand is the amount of energy consumed to heat up the building in a year per m^2.

Formula: $Q_d = Q_h * 3600/3600000$, where (Eq.4)

Q_h is the heating load.

Transmission losses | Q_T [kWh]:

The transmission loss is the amount of energy lost (or gained) between two points by conduction.

Formula: $Q_T = 0{,}024 * L_T * HGT$, where (Eq.5)

Q_T is the transmission loss/gain,

L_T is the total conductance,

HGT are the heating degree days.

Losses due to air change | Q_v [kWh]:

The total loss due to air change is the amount of energy lost via infiltration and ventilation between the interior and exterior of the building.

Formula: $Q_V = 0{,}024 * L_V * HGT$, where (Eq.6)

Q_V is the natural infiltration loss,

L_V is the guiding value for ventilation ($L_V = 0{,}33*n*V_n$),

HGT are the heating degree days.

Solar gains | Q_s [kWh]:

The solar gain is the amount of energy gained via solar radiation.

Formula: $Q_s = \Sigma(A_{gi} * I_j * f_{si} * g_{wj})$, where (Eq.7)

Q_s is the solar gain,

A_{gi} is the glass area,

I_j is the intensity of the solar radiation (depends on the location and orientation of the building),

g_{wj} is the effective transmittance.

Internal gains | Q_i [kWh]:

The internal gains are the amount of energy gained from occupants, lighting and equipment.

Formula: $Q_i = 0{,}024 * q_i * BGF * H_T)$, where (Eq.8)

Q_i is the monthly internal gain,

q_i is the heat flow density,

BGF is the gross floor area,

H_T is the total of heating days.

3.4. EDSL TAS SIMULATION PROGRAM

To determine the thermal performance of the vernacular houses of Bukovina, a series of simulations were carried out. The chosen thermal simulation software was EDSL (Environmental Design Solutions Limited) Tas, Version 9.4.1. It is a 3D based simulation tool that is capable of performing dynamic thermal simulations, giving engineers the opportunity to predict the behavior of a building in terms of energy consumptions, CO_2 emissions, operating costs and occupant comfort (EDSL 2014)

3.5. DESCRIPTION OF THE HOUSES

3.5.1. House 1: "Rosu" House

The "Rosu" House stems from the town with the same name, Rosu, located in the Dorna ethnographic area. The house dates from the late 19th century, and its last owner is Varvara Negrea. The house is currently located in the Bukovina Village Museum since 1992.

The house impresses with its size, and it used to belong to wealthy householders, evidence to that being the two stoves with urban-inspired elements and the wide entrance pavilion. The interiors are furnished with decorative and utilitarian objects specific to the Dorna region.

The construction was intended for housing, the layout is the room-hallway-room type, which is specific for the mountainside region of Bukovina. The substructure of the house is made of river rocks, with a cyclopean concrete foundation and river rock masonry. The walls consist of fir planks carved with a rectangular profile concluded at the corners under the "German" construction technique. Around the windows the walls have a clay overlay and a whitewash, while the rest of their surface is covered with a thin layer of gray clay.

The hipped roof is built with shingle wrapper beaten in superimposed rows and it has two smoke outlets on the front side. The floor is made of fir planks and the interior walls are made of brick masonry with mortar cement.

The house has two rooms, a hallway and a porch. The entrance hall is large, and from there the two rooms and pantry on the left can be accessed. Behind the house (on the northern side) there are two separate pantries, which can be accessed through the porch (on the left) and kitchen (on the right). The porch is set in the middle of the south façade, with a covered pavilion. On the right side under the stairway there is a separate entrance leading to the basement.

The room on the left, also known as “the big house”, is a space for keeping valuables, destined to lifetime or yearly celebrations. This is the place to keep the chest of dowry with the finest fabrics for girls to marry. On the southern side there is the bed made of wooden planks, and on the northern side the bed for keeping the woven fabrics of dowry.

The room on the right side is the living room (with kitchen and bedroom functions), where the daily activity would take place. There is an oven (which takes up one quarter of the room area) with a fireplace and the tools needed to prepare food. Following is the bed rest, on which pillows are stacked. Above the bed, garments and textiles are hanging on the wall. Along the eastern and southern walls, there are wooden plank beds covered with fleece. Near the windows on the south side there is a table covered with a tablecloth. The eastern wall is adorned with three icons. At the entrance, on the western wall, in the corner formed between the door and the south wall there is a dish rack sitting on logs, on which plates and bowls are stacked, that have decorations specific to the Dorna region. (Bukovina Village Museum Book 2012)

Figure 10 Rosu House images. Exterior (left) and interior (right)
(photo archive of the author)

3.5.2. House 2: “Cacica” House

Originally the house was located in the town Cacica, in the ethnographic area of Humor. The house dates from 1900, and its last owner was Maria Lazarovici. The house was rebuilt in the Bukovina Village Museum in 2002.
The layout of the house is the room-hallway-room type, specific to the Bukovina mountainside area, and it also has a pantry under the lower slope of the roof. The substructure is made of river rocks with mortar binder, and the foundation is made of cyclopean concrete and river rock masonry. The superstructure is constructed of fir planks carved with a rectangular or round profile, joined at the corners according to the “German” construction technique.

Figure 11 Cacica House images. Exterior (left) and interior (right) (photo archive of the author)

The walls are covered in clay and are whitewashed around the openings. The house has the anthropomorphic motif (man head) at the gate pillars, and the zoomorphic one (horse head) at the ends of the rafters. The hipped roof is covered in pine shingle wrapper, it is beaten in overlapping rows on each side and on the front side it has two smoke outlets. The floor is made of stabilized clay.
The house has a porch on the main façade. The entrance is made through the hallway, which then provides the access to the two rooms. On the right side there is the “big house”, the rectangular-shaped event and storage room, and on the left side there is the L-shaped room which serves as a living room and kitchen. On the left side of the main entrance there is the access to the pantry. (Bukovina Village Museum Book 2012)

3.5.3. House 3: “Vicov” House

The house in the town of Lower Vicov, ethnographic region of Radauti dates from the early 20th century. A coin dating from the year 1924 was found at the foundation of the house. Its last owner was Ion Chifan. The house was rebuilt in the Bukovina Village Museum in the year 2001, the objective being opened to the public since the 14th of June, 2006.

The plan layout of the house consisted of two rooms and a storage space under the extended slope of the roof. The superstructure is made of fir planks joined in the “flint” construction technique. The entire surface of the walls is covered in clay and then whitewashed.

The hipped roof is made of pine shingle wrapper beaten in superimposed rows, and it has two dormers on the front board.

At the ends of the rafters that support the roof shingle there is the zoomorphic motif present ("horse head"). Under the extended slope of the roof a spoon workshop was built, which was a popular type of craft in the area. (Bukovina Village Museum Book 2012)

Figure 12 Vicov House images (photo archive of the author)

3.5.4. House 4: “Roata” House

One of the first houses purchased by the Bukovina Village Museum is a house from the town of Campulung Moldovenesc, dating from the second quarter of the 19th century. Its last owner was Gabriel Roata, therefore the name “Roata” House. It was rebuilt in the museum in 1976 and is one of the earliest types of dwelling from Bukovina.

The plan layout of the house is of the hallway-room type, a widely used traditional layout from the region of Campulung Moldovenesc. The substructure is made of massive river rocks with mortar binder, with a cyclopean concrete foundation and river rock masonry. The superstructure is made of twigs and fir wood barrels joined in lapel system. The walls are plastered and painted over several times.

The hipped roof is made with pine shingle wrapper, beaten in superimposed rows and it has a skylight on the front board. The roof is high, achieving a ratio of 2/3 of the height of the house. The floor is made of compacted earth.

The house floor area is small (6,30m x4,20m), it has one entrance door and three windows. The door is made of solid wood boards and is secured by wood hinges. Also, the door has a lock and a lever: a classic lock made of hardwood, being driven by a massive key, all made of wood.

The entrance hall is the space with connection to the exterior, and also the space that was being used for storage of food and household items such as wooden pails, box of flour, drums, mortar etc. In the back there is a pit that was used for keeping potatoes, beet and fruit in winter.

From the entrance hall one can access the room. On the left side of the entrance there is the stove, which has a traditional hearth area. Between the oven and the front wall there is a bed made of massive wooden boards over a beam.

On the inside there are household objects such as ceramic pots and bowls. Hanging on the wall, on the bed or near the icons, several fabrics made of wool and hemp are displayed: carpets, rugs, wall towels wedding veils. (Bukovina Village Museum Book 2012)

Figure 13 Roata House images. Exterior (left) and interior (right) (photo archive of the author)

3.6. CONSTRUCTION AND MATERIALS

As Bukovina is a mountainside area, rich in fir woods, and also abundant in loamy soil regions, in building the traditional vernacular houses, people made use of the local materials, therefore combining fir wood and clay.

3.6.1. Foundation

The substructure of the vernacular houses is reliant on river rocks with mortar binder and the foundation is made of cyclopean concrete and river rock masonry. The substructure goes to about one meter in the ground, around 45 cm above the surface and its width is 60 cm.

3.6.2. Slab

The vernacular houses only have a ground floor, in isolated cases they also have a cellar. The ground floor slab, depending on the period the house was built in and the social status of the former owners, is made of either compacted ground, compacted ground and stabilized clay or compacted ground, stabilized clay and fir planks.

3.6.3. Exterior walls

The exterior bearing walls are made without exception of fir wood, either planks or barrels. They are joined at the corners in lapel, flint or in the “German” system. Around the doors and windows the walls have frames made by a superimposing layer of clay and another one of whitewash. Some houses have the same two layers over the entire surface of the wall on the exterior, some have them on the interior and some use a more complex system to ensure a better air tightness: on top of the fir wood logs (that have the width of 15 to 20 cm) two rows of fir wood slaps are superimposed, positioned at a 45 respectively 135 degree angle. On top of that a 22 mm grey clay layer is applied, to ensure compactness. As the clay is breakable, the wood slaps act as a structure for this layer. The next two layers, a 2 mm yellow clay plaster and the 5 mm limestone layer are used as finishing.

3.6.4. Interior walls

The interior walls are usually made of fir wood planks or logs of the same type and width (ranging from 15 to 25 cm) as the exterior walls. However, in some cases of wealthier families and newer houses, the interior walls have the structure made of whole brick masonry, with a width of 22 cm, and mortar binder on top of which a 1.5 to 3 mm layer of lime plaster is added on each side.

3.6.5. Roof

The hipped roofs have very slanted slopes to easily evacuate the large amounts of rainwater and to prevent the snow from accumulating on them. This makes the roof very tall and respective to proportions it reaches 2/3 of the height of the entire house. The attic area is not inhabited, but used for food storage. The smoke from the stove is directly released into the attic, and is then evacuated throughout the smoke outlets present on one of the slopes of the roof. This way, in winter there is a warm air cushion, which acts as a thermal buffer between indoor and outdoor temperatures. The structure is made of fir wood rafters (14x14 cm) and decking (a 22 mm layer), then rows of wooden slats every 20 cm on top of which pine shingle wrapper is beaten in superimposed rows. It also has either one or two smoke outlets on the front side.

3.7. THERMAL PROPERTIES

The fir wood, the most used building material, has a thermal conductivity factor of $\lambda = 0.115$ W/m^{-1} K^{-1}. With fir wood walls ranging in thickness from 15 to 25 cm, with extra clay layers in some cases, it is presumable that with few changes, the vernacular houses could potentially ensure a thermal comfort that would meet contemporary requirements. In the case of a 30 cm wall made of 25 cm fir wood and a 5 cm layer of lightweight clay (which has a thermal conductivity of $\lambda = 0.33$ W/m^{-1} K^{-1}), its heat transfer coefficient is calculated at 0.457 W/m^{-1} K^{-1}. The U-Value requirement for heat-transferring walls is of 0.35 W/m^{-1} K^{-1}, according to OIB-RL 6 from 2015.

The interior walls are made of the same fir timbers as the exterior walls, in most cases. Only one of the case study houses has interior walls made of brick masonry ($\lambda = 0.6$ W/m^{-1} K^{-1}) with a layer of lime plaster ($\lambda = 0.7$ W/m^{-1} K^{-1}) on each side.

The doors, door frames and window frames are also made of the same fir wood with a thermal conductivity factor of $\lambda = 0.115$ W/m^{-1} K^{-1}. The window panes are made from glass which has a conductivity of $\lambda = 1.0$ W/m^{-1} K^{-1}. The ground floor slab, made of river rocks, sand and clay, has a a thermal conductivity factor of $\lambda = 2.08$ W/m^{-1} K^{-1}, whereas the one made of fir planks has the value of only $\lambda = 0.65$ W/m^{-1} K^{-1}.

After a closer look at the construction layers and the thermal properties of the materials used, one may assume that the traditional houses from Bukovina might respond properly in terms of thermal comfort.

3.8. THERMAL ENVIRONMENT STANDARDS FOR RESIDENTIAL BUILDINGS

3.8.1. Romanian thermal environment standards

In the European Union, the energy consumption of buildings accounts for 40% of the total consumption, and 36% of carbon dioxide emissions.

As far as requirements of heating fuel are concerned, new buildings have an annual consumption of three to five liters of oil for heating one square meter, whereas older buildings need about 25 liters, the maximum requirement sometimes reaching 60 liters.

In the European Union, over 35% of buildings are over 50 years old, hence increasing energy efficiency would reduce energy consumption and carbon dioxide emissions by about 5%.

In Romania, most of the dwellings are more than 50 years old and do not meet the thermal requirements to ensure proper energy performance. Thus, about 55% of the total energy consumption of the apartments, respectively 80% of the individual houses is intended for heating.

In order to increase the energy efficiency of buildings, the building owners can adopt the following recommendations:

Ensure the sealing of all doors and windows in unheated spaces; Thermally insulating the attic floor or roof, exterior walls, replacing old windows with energy efficient windows; Increasing the yield of heat production in case of local heating with stoves through changing solid or liquid fuel with gaseous fuel; Increasing the efficiency of the heating system by replacing the stoves with a heating system plant; Correctly ventilating kitchens and bathrooms to ensure the fresh air requirements for personal comfort; Regular cleaning of heating systems (boilers, stoves, chimneys); Providing radiators with thermostatic head, respectively heating system with adjustable clock, programmable; Periodic washing of radiators and heat distribution columns inside the building; Metering hot water consumption; Eliminating hot water loss by replacing faulty fittings; Equipping the living space with appliances of the upper energy class (A or higher), using low-energy luminaires; Using blinds or shutters to thermally insulate windows; Using solar systems for the production of domestic hot water. (Tamas, Tartan 2015).

One Romanian standard addressing thermal comfort is “SR 1907-2 Heating plants. Design heat requirements computation for buildings. Design conventional indoor temperatures.” This standard establishes conventional indoor temperature for calculations meant to determine the heat demand of different types of buildings. Conventional indoor temperatures for heated rooms in residential buildings are presented in Table 2.

Table 2 Conventional indoor temperatures for heated rooms in residential buildings (SR 1907-2: 2014)

Nr.	**Room destination**	**Conventional indoor air temperature [°C]**
1	Living room and hallway	20
2	Lobby	18
3	Bathroom and shower	22
4	Kitchen	18
5	Toilette within the apartment	18
6	Toilette outside the apartment	15
7	Stairs and corridors outside the apartment	10
8	Entrance (Wind fang)	12
9	Laundry room	15
10	Dryers in housing blocks	20
11	Underground car parking	10

The Law No. 372/2005 promotes the increase in energy performance of buildings, taking into account outdoor climatic conditions, locations and indoor comfort conditions, to ensure optimal costs, an optimal energy performance, and to improve the urban aspect of the settlements. The minimum U-values are regulated as shown in Table 3.

Table 3 Minimum corrected thermal resistances (Order No. 2641/2017, addition to law No. 372/2005)

Building component	**U-value [W.m^{-2}.K^{-1}]**
External walls (excluding fenestration, including adjoining walls of open joints)	**0,56**
Exterior carpentry	1,30
Slabs above the last level, under terraces or bridges	0,20
Slabs over unheated basements and basements	0,35
Walls adjacent to closed joints	0,90
Slabs that separate the building from the exterior at the bottom (at bowlines, passage ways, etc.)	0,22
Slabs on the ground (over systematized land quota)	0,22
Slabs at the bottom of heated basements or semi - basements (under systematized land quota)	0,21
External walls, under CTS, to semi-basements or heated basements	0,35

The technical regulation C 107-2005 on the thermal calculation of building construction elements sets out the method to determine the global thermal insulation coefficient (G) which expresses the total heat loss in residential buildings. The regulation also includes the normed maximum values of global thermal insulation coefficients (GN) that are appointed to residential buildings. The air change rates in residential buildings presented in C 107-2005 are regulated according to INCERC (The National Institute of Research and Development in Construction, Urbanism and Sustainable Development) as follows:

Table 4 Air change rates in residential buildings (C107-1-3-2005)

Building category	**Degree of sheltering**	**Degree of permeability**		
		high	**medium**	**low**
Individual buildings (single family houses, row houses etc.)	not sheltered	1,5	0,8	0,5
	moderately sheltered	1,1	0,6	0,5
	sheltered	0,7	0,5	0,5

where,
Degree of sheltering:

not sheltered:	very high buildings, buildings on the outskirts of cities and in markets;
moderately sheltered:	buildings inside cities with at least 3 buildings nearby;
sheltered:	buildings in the city center, buildings in forests.

Degree of permeability:

high:	buildings with external joinery without sealing;
medium:	buildings with external joinery with sealing gaskets;
low:	ventilated buildings with external joinery provided with special sealing arrangements.

3.8.2 European thermal environment standards

The indoor environment has a major impact on the health, productivity and comfort of occupants. The parameters needed to ensure thermal comfort influence the heating demand of buildings. These issues are addressed in parallel to the pursuit of improving the energy performance of buildings. However, 10,8% of the European population have been reported to suffer from discomfort in winter due to temperatures that are inadequately low (BPIE 2014).

An indicator of thermal comfort, indoor air temperature is regulated in the standard EN 15251-Indoor Environmental Criteria. Table 5 shows the recommended temperatures for residential spaces.

Table 5 Recommended design values for indoor air temperatures (EN 15251)

Type of space	**Category**	**Operative temperature [°C]**	
		Heating ~ 1.0 clo	Cooling ~ 0.5 clo
Residential buildings: living spaces (bedrooms, drawing rooms, kitchen etc.) sedentary ~ 1.2 met	I	21,0	25,5
	II	20,0	26,0
	III	18,0	27,0
Residential buildings: other spaces (boxrooms, halls etc.) standing, walking~ 1.6 met	I	18,0	
	II	16,0	
	III	14,0	

The Austrian standard ÖNORM B 8110 2011 recommends the average indoor temperature of 20 °C for housing, office and school buildings.
Concerning U-values of the building elements, the requirements of the Austrian standard OIB RL. 6 2015 are as shown in Table 6.

Table 6 Requirements for heat-transferring components (OIB RL. 6 2015)

Building component	**U-value [W/m^{-1} K^{-1}]**
Exterior walls	0,35
Exterior walls to unheated enclosures (e.g. garage)	0,60
Partition walls between heated and unheated spaces (e.g. hallway)	0,90
Windows	1,40
Doors	1,70
Roofs	0,20
Floor slab to basement	0,40
Floor slab against the ground	0,40

3.9. CHOICE OF THERMAL INSULATION MATERIALS

Energy consumption is increasing steadily worldwide, due to the increase of population and improvement of the quality of living. The building sector, being responsible for 40% of the primary energy consumption, is a major influencer in this matter, and therefore presents the potential to substantially reduce CO_2 emissions. One way to achieve this is to reduce the heat transmission losses by means of thermally insulating the building envelope, while also reducing the environmental load of the building stock. (Saadatian et al. 2016)

In the case of building rehabilitation, the quality of the thermal insulation material used has a large impact on the overall performance of the building. Using high quality thermal insulation materials presents several advantages, such as: lowering heating loads which in turn generate financial savings, protection against overheating, eliminating thermal bridges, protecting the structural elements from external factors, soundproofing, achieving a superior energy class. (Eftimie 2017)

From a sustainability point of view, buildings are not only being reviewed based on energy demand, but also on the embedded energy of the materials used, and their ecological properties. Therefore, the use of ecological materials has become crucial.(Korjenic et al. 2015)

Currently, the most used material for thermal insulation is polystyrene. The thermal insulation systems based on polystyrene are the most popular for building renovations, due to their reduced costs and the highest return on investment compared to other building insulation materials (Eftimie 2017).

However, there are several other aspects that need careful consideration before deciding on an insulation material.

Considering the fact that one of the main occupations that farmers have in rural Bukovina is sheep breeding, sheep wool insulation was proposed as an alternative to polystyrene. This choice is in line with the ecological design approach, which aims to achieve environmental harmony, by making use of natural and locally available materials.

Sheep wool presents several advantages, among which:

- It is a very good insulator, with a conductivity ranging between 0,035 and 0,04 $W/m^{-1} K^{-1}$;
- It is natural, renewable and sustainable;
- It presents no hazard to human health
- It is hygroscopic – it can absorb up to 33% of its weight in moisture without having its thermal performance compromised
- It is flame resistant – it has a very high ignition temperature of 570-600 °C, a high limiting oxygen index, low heat of combustion, does not melt – and is self-extinguishing
- It is static resistant, due to the fact that it absorbs moisture from the air
- It absorbs and reduces noise levels
- It is dirt resistant – it does not attract dust from the air and the structure of the fiber keeps dirt from penetrating into the fabric (Korjenic et al. 2015)

To assess the thermal response of the examined buildings, were they to be renovated, the structure of the existing walls was fitted using an interior insulation of sheep wool in the case INS_SW and expanded polystyrene in the case INS_P. The typical wall structure is shown in figure 60.

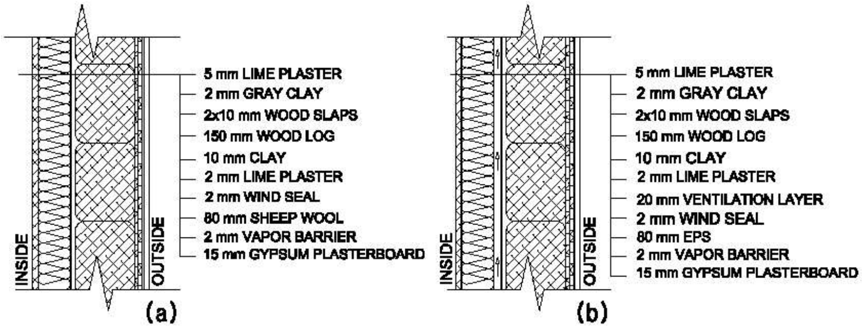

Figure 14 The structure of an existing wall, renovated using an interior insulation with sheep wool (a) and with expanded polystyrene (b).

Placing the insulation on the inner side of the outside walls was a decision dictated by the desire to not interfere with the appearance of the houses. Due to its hygroscopic nature, sheep wool is suitable for such an intervention. However, a careful construction planning is required to avoid any permanent condensation within the insulation layer, or at least provide sufficient dry-out-time, in case it happens. Polystyrene however presents the risk of developing mildew on its warm side. To avoid this, a 2 cm ventilation layer was required between the polystyrene insulation board and the existing wall structure.

4. Dynamic thermal Simulation

Four houses were selected as case studies, in order to perform the thermal simulations. The houses vary in size, number and function of rooms. They all date from the same period, late 19th century – early 20th century.

The simulations are carried under five different cases, in order to assess the thermal response of the buildings. The Base Case (BC) simulates the buildings in the state that they are currently in, with an air change rate of 0,62h^{-1}(Panzhauser et al. 1992). In the Weatherization case (W), the building air change rate was changed to 0,4 h^{-1} (ONORM B-8110:5 2011), in order to get the thermal response of weatherized buildings, yet the original windows were not changed. The Improved Weatherization (W+) case is replacing the old windows with thermally efficient ones, together with the weatherization of the houses. In the fourth and fifth scenarios, the building envelope U-values were improved by adding a layer of thermal insulation of sheep wool (INS_SW), respectively polystyrene (INS_P).

Table 7 General data of the examined buildings

	House 1	**House 2**	**House 3**	**House 4**
Country, region	Romania, Bukovina			
Village	Rosu	Cacica	Vicov	Cl. Mold.
Floors	B (u)+ GR FL+roof (u)	Ground floor + roof / attic (unheated)		
Construction period	late 19th – early 20th century.			
Wall construction	Wood log structure with clay overlay			
Gross heated area	98,2 m^2	78,3 m^2	54,2 m^2	32,2 m^2
Gross heated vol.	245,5 m^3	223,1 m^3	135,5 m^3	83,7 m^3
Building envelope area	98,6 m^2	111,5 m^2	74,7 m^2	52,1 m^2
Area of the opaque elements of the building envelope	91,9 m^2	109,3 m^2	71,2 m^2	51,9 m^2
Area of the transparent elements of the building envelope	4,1 m^2	2,2 m^2	1,5 m^2	0,2 m^2

The areas presented in Table 7 are of the houses after they were fitted with a bathroom (cases W, W+, INS_SW and INS_P).
The parameters for internal heat gains emanated by equipment, light and occupants are chosen according to ÖNORM B 8110-5:2011, q_i=3,75 $W.m^{-2}$.
According to their use, the room temperatures were set to the values shown in Table 8.

Table 8 Adopted room temperatures (in accordance with SR 1907-2)

Temperature [°C]	**Room type**
20	occupied for longer periods of time (living room/bedroom)
22	bath and shower rooms
18	occupied for short periods of time (kitchen, hallway, pantry)

Table 9 Internal gains of the examined buildings

INTERNAL CONDITIONS		
CASE	**BC**	**W, W+, INS_SW, INS_P**
Air change rate	0,62 h^{-1}	0,4 h^{-1}
Lighting gain	1,75 $W.m^{-1}$	
Occupancy sensible gain	1,00 $W.m^{-1}$	
Occupancy latent gain	-	
Equipment sensible gain	-	
Equipment latent gain	1,00 $W.m^{-1}$	

Table 10 Settings of the thermostat

THERMOSTAT SETTINGS	
Temperature upper limit	26,5°C
Temperature lower limit	according to Table 8
Humidity upper limit	50%
Humidity lower limit	40%
Weekday schedule	23:00-06:00=0, 06:00-09:00=1, 09:00-16:00=0, 16:00-23:00=1
Weekend schedule	23:00-06:00=0, 06:00-23:00=1

4.2. BASE CASE

4.1.1. Simulation of House 1

Casa "Rosu" has the largest surface of all four chosen examples. Its net area is 71,5m^2 and its gross area is 92,2 m^2. The house was surrounded by low rise annex buildings which had no influence in terms of shading. The plan is simple, of rectangular shape, with the dimensions 12,5 x 7,4 m. On the -1 level there is a 47,0 m^2 net area cellar. The pitched roof with a 33° angle is not habitable, but only used for storage. The net areas of the rooms in house 1 are as follows:

- Hallway……………………………………….....……....…10,1 m^2
- Living room……………………………………..……..……..16,6 m^2
- Kitchen……………………………………………….......….23.7 m^2
- Storage room…………………………………………...….10,4 m^2
- Pantry……………………………………………….……..…..10,8 m^2

Figures 15 and 16 depict the floor plan and the cross section of House 1 in its current state.

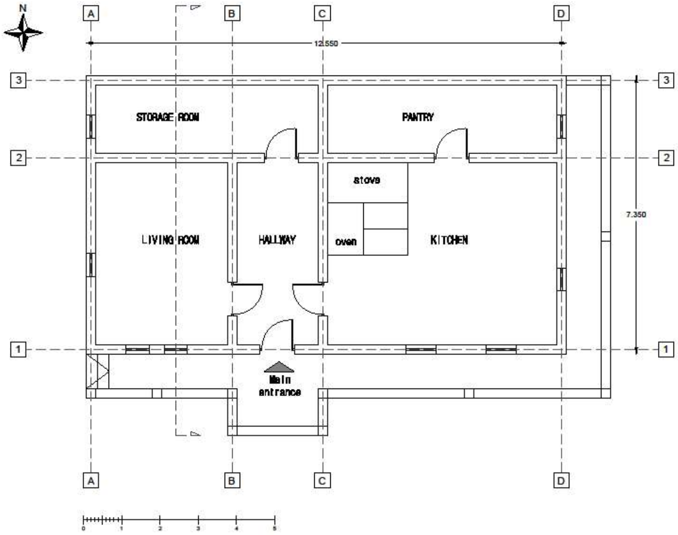

Figure 15 House 1 floor plan

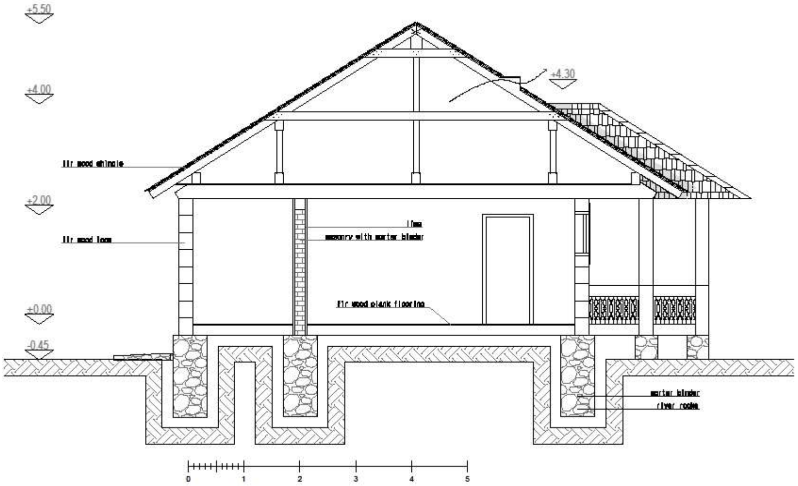

Figure 16 House 1 section

4.1.2. Simulation of House 2

“Cacica” house is the second largest house of the four chosen examples. Its gross area is of 78,3m^2 while the net area sums 66,5m^2. It is from the Cacica village in the region of Gura Humorului, with a latitude, longitude and altitude of 47,617, 25,883 and 698 m respectively. It has in total four rooms, of which three are heated. In terms of shading, the surrounding low rise buildings wield no influence. The dimensions of its simple rectangular plan is of 7,9 m x 9,9 m. The pitched roof with a 33° slant is only used for storage and not for habiting. The room net areas are as follows:

Hallway	7,3 m^2
Living room	23,2 m^2
Kitchen	14,0 m^2
Pantry	21,9 m^2

Figures 17 and 18 depict the floor plan and the cross section of House 2 in its current state.

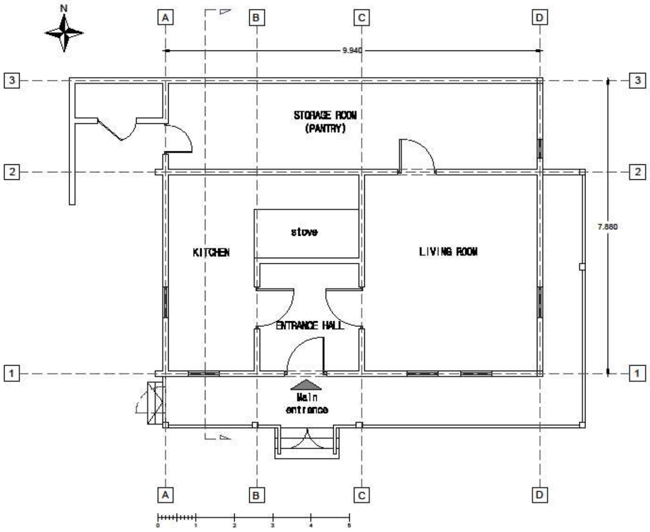

Figure 17 House 2 floor plan

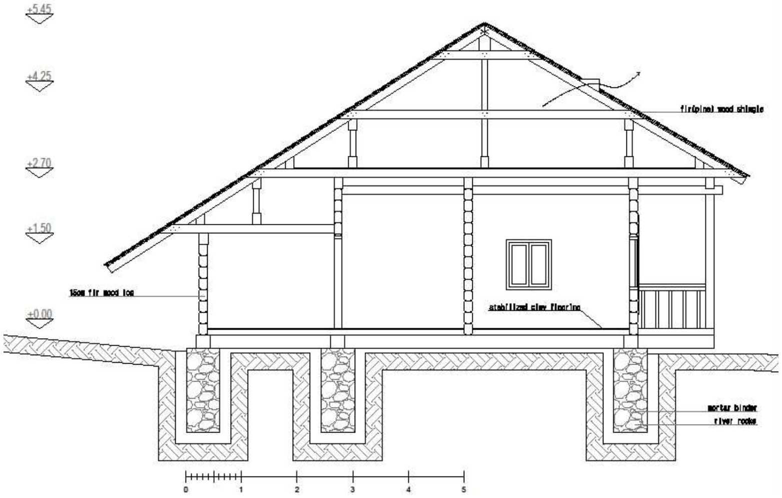

Figure 18 House 2 section

4.1.3. Simulation of House 3

"Vicov" house was located in the rural settlement Vicovul de Jos, near Radauti with the latitude, longitude and altitude of 47,867, 25.617 and 597 m respectively. It is a rectangular shaped house with three rooms: kitchen, living room and a workshop. Unlike the two prior examples, this house does not have the unheated corridor in between the living room and the kitchen. However it has a workshop, which is placed on the western side of the house. The plan dimensions are 5,1 m x 9,0 m. The gross area is of 46,1m^2 and the net area is of 36,8m^2. The roof is slanted at 40° and the attic is only used for storage. The neighboring low rise buildings do not provide any influence in terms of shading. The spaces and their net areas are as follows:

• Living room	14,9 m^2
• Kitchen	13,3 m^2
• Workshop	8,6 m^2

Figures 19 and 20 depict the floor plan and the cross section of House 3 in its current state.

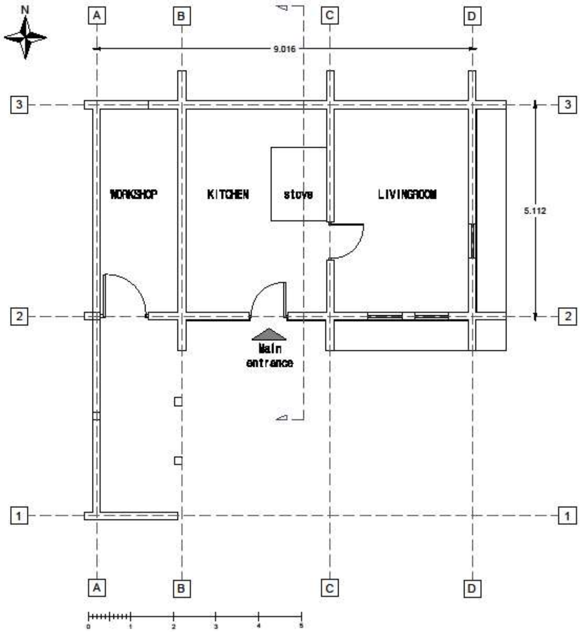

Figure 19 House 3 floor plan

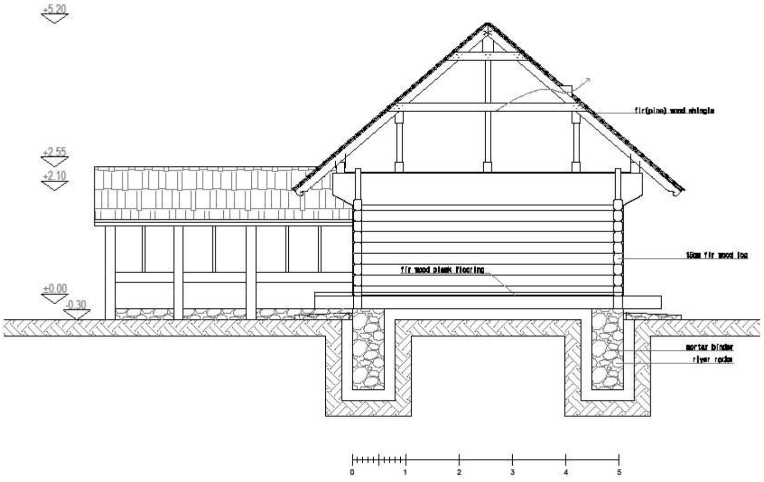

Figure 20 House 3 section

4.1.4. Simulation of House 4

Roata house is the smallest of the four chosen examples. It is made of only one room and the entrance hallway. The dimensions of its simple rectangular floor plan are 6,3 m x 4,2 m. The gross area is 27,0 m^2 and net area is 21,6 m$^{2.}$ The house was situated in Campulung Moldovenesc, Humor region. The coordinates for the location are: 47,5308, 25,5514 and 646 m for latitude, longitude and altitude respectively. The pitched roof has a slant of 44° and is, as in the previous cases, the attic is only used for storage. The spaces and their areas are as follows:

- Living room…………………………………..……….....…14,4 m^2
- Hallway...…………………………………...…...……..……7,2 m^2

Figures 21 and 22 depict the floor plan and the cross section of House 4 in its current state.

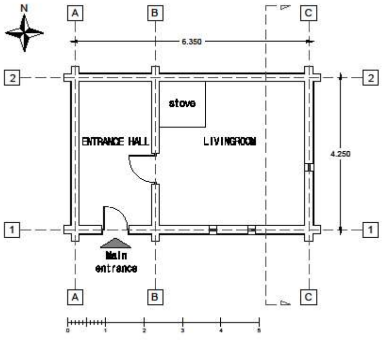

Figure 21 House 4 floor plan

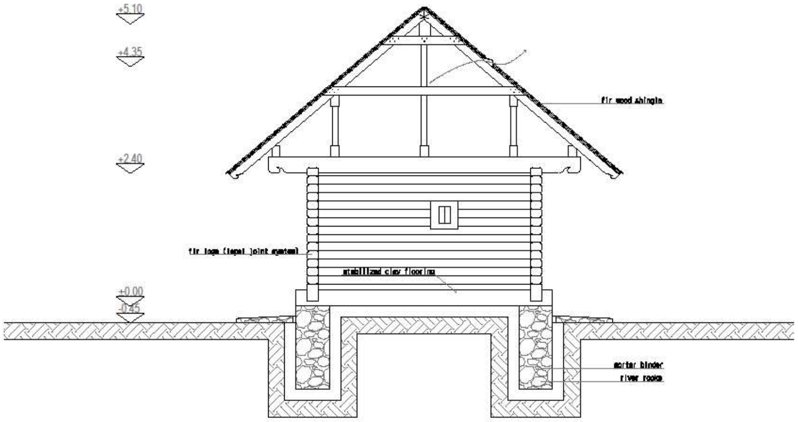

Figure 22 House 4 section

Table 11 U-values in the examined buildings, BC

Building element	**House 1**		**House 2**	**House 3**		**House 4**
	$[W.m^{-2}.K^{-1}]$		$[W.m^{-2}.K^{-1}]$	$[W.m^{-2}.K^{-1}]$		$[W.m^{-2}.K^{-1}]$
Outside wall	0,42		0,65	0,59	0,67**	0,50
Ground floor slab	1,29*	0,54	0,59	0,61		0,57
Ceiling to attic	1,65		1,09	1,43		1,50
Window	5,68		5,68	5,68		5,68

* *Ground floor slab over unheated basement*
** *Outside wall of the workshop*

Table 11 shows the U-values of the examined buildings in their current state (base case). Except for the U-values of the outside walls of House 1 and House 4, the U-values of all the other building elements are not in the recommended range according to the Romanian building regulation Order No. 2641/2017, addition to law No. 372/2005 (Table 3)

4.2. W, W+, INS_SW, INS_P

To meet the living standards of today, the houses had to be brought up to date in terms of facilities. Thereby, for the second set of simulations they are considered to each be fitted with a bathroom (marked with a hatch in the floor plans, Figures 22-25) with a toilet, sink and a shower cabin. To keep in line with the vernacular house concept, the new constructions walls are made of mainly local natural materials. *“The most appropriate materials for insulating traditional constructions are natural fiber based materials such as sheep’s wool (…) as they have the following performance characteristics: they are hygroscopic (they can absorb but also release excess moisture); they retain their insulation qualities even when damp; they are non-hazardous fibers”* (Pickles 2016). However, for the sake of an accurate comparison between sheep wool insulation and polystyrene, the insulation materials were adopted accordingly in the INS_SW and INS_P cases.

The structure of the new walls contains the following layers:

Table 12 Material layers of the new external walls

Layer	***Width (mm)***	***Conductivity (λ)***
Gypsum plasterboard	15	0,22
Vapor barrier	1	0,17
Sheep wool/EPS	80	0,0385 / 0,035
Chip board	22	0,110 / 0,035
Sheep wool/EPS	80	0,0385
Fir wood planks	24	0,115
Yellow clay	5	0,288
Gray clay	3	0,330

4.2.1. Simulation of House 1

Figure 23 depicts the floor plan of House 1 after being fitted with a bathroom. The addition to the floor plan is marked with a hatch in the drawing. This is the floor plan used for the simulations in the cases W, W+, INS_SW and INS_P.

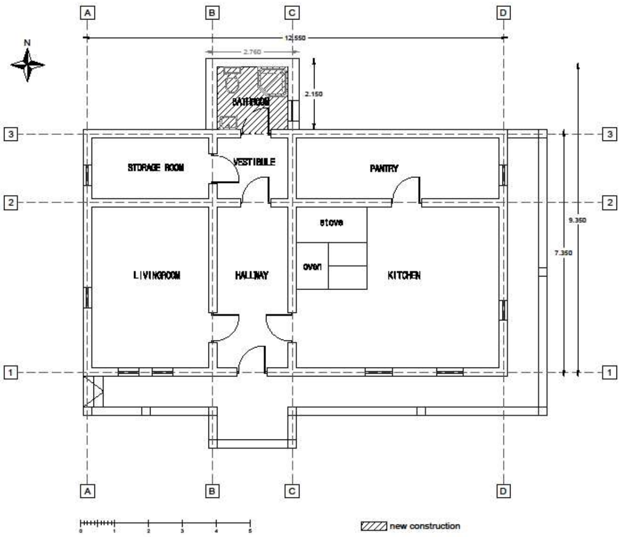

Figure 23 House 1 new floor plan

4.2.2. Simulation of House 2

Figure 24 depicts the floor plan of House 2 after being fitted with a bathroom. In this case no addition was needed, as the floor plan allowed for the pantry space to be reallocated in order to have a bathroom within the initial building envelope. The reallocated space was marked with a hatch in the drawing. This is the floor plan used for the simulations in the cases W, W+, INS_SW and INS_P.

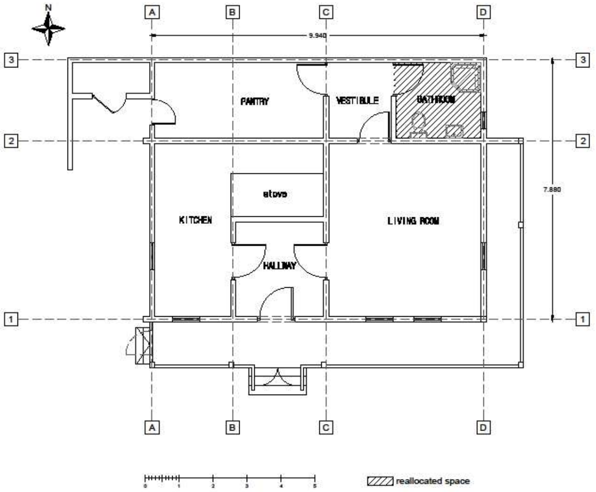

Figure 24 House 2 new floor plan

4.2.3. Simulation of House 3

Figure 25 depicts the floor plan of House 3 after being fitted with a bathroom. The addition to the floor plan is marked with a hatch in the drawing. This is the floor plan used for the simulations in the cases W, W+, INS_SW and INS_P.

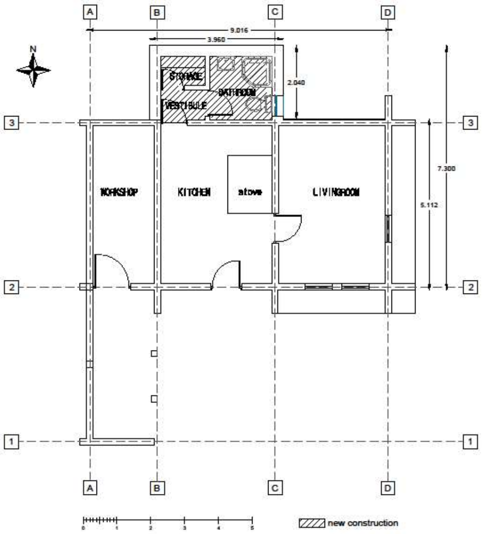

Figure 25 House 3 new floor plan

4.2.4. Simulation of House 4

Figure 26 depicts the floor plan of House 4 after being fitted with a bathroom. The addition to the floor plan is marked with a hatch in the drawing. This is the floor plan used for the simulations in the cases W, W+, INS_SW and INS_P.

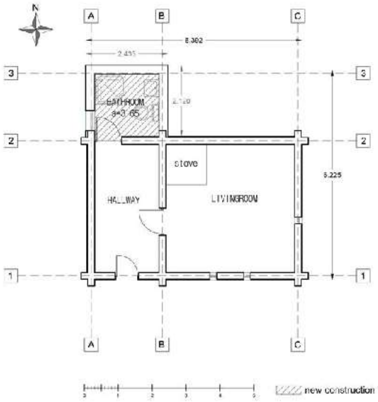

Figure 26 House 4 new floor plan

Table 13 shows the U-values of the examined buildings after being renovated (case INS_SW and case INS_P). The values are in the recommended range according to the Romanian building regulation Order No. 2641/2017, addition to law No. 372/2005 (Table 3)

Table 13 U-values in the examined buildings, INS_SW / INS_P

Building element	**House 1**		**House 2**		**House 3**		**House 4**	
	$[W.m^{-2}.K^{-1}]$		$[W.m^{-2}.K^{-1}]$		$[W.m^{-2}.K^{-1}]$		$[W.m^{-2}.K^{-1}]$	
	SW	P	SW	P	SW	P	SW	P
Outside wall house	0,22	0,18	0,27	0,21	0,26/ 0,27**	0,21/ 0,22**	0,24	0,23
Outside wall annex	0,20	0,19	-		0,20	0,19	0,20	0,19
Ground floor slab	0,12/ 0,11*	0,11/ 0,10*	0,12	0,10	0,11	0,10	0,12	0,10
Ceiling to attic	0,19	0,18	0,14	0,13	0,19	0,18	0,16	0,15
Window	1,18		1,18		1,18		1,18	

* *Ground floor slab over unheated basement*
** *Outside wall of the workshop*

5. Results and discussion

In this chapter the results of the dynamic simulation are presented and discussed. These are organized in three parts, as follows:

- In the first part, overview graphs compare the dynamic simulation results of the four examined buildings, in terms of the most influential parameters on their thermal performance. Presented and discussed graphs for annual heating demand, transmission losses, total losses due to air change, solar gain and internal gain.
- The second part addresses the problem of overheating. Graphs depicting the annual energy consumption for heating and cooling are shown, and results are compared throughout the four cases, as the building envelope of each of the four examined houses gets thermally improved.
- The third part focuses on the comparison between the two chosen insulation materials: sheep wool and polystyrene. Presented and discussed are graphs showing the thermal performance of the four examined buildings with each of the two materials, embodies energy and global warming potential, and a life cycle analysis is performed.

In the graphs, the following abbreviations were used for the different cases: BC = Base case, W = Weatherization, W+ = Weatherization + new windows, INS_SW = Sheep wool insulation and INS_P = Polystyrene insulation.

5.1 HEATING DEMAND

Figure 27 illustrates an overview of the annual heating demand in the four examined buildings.

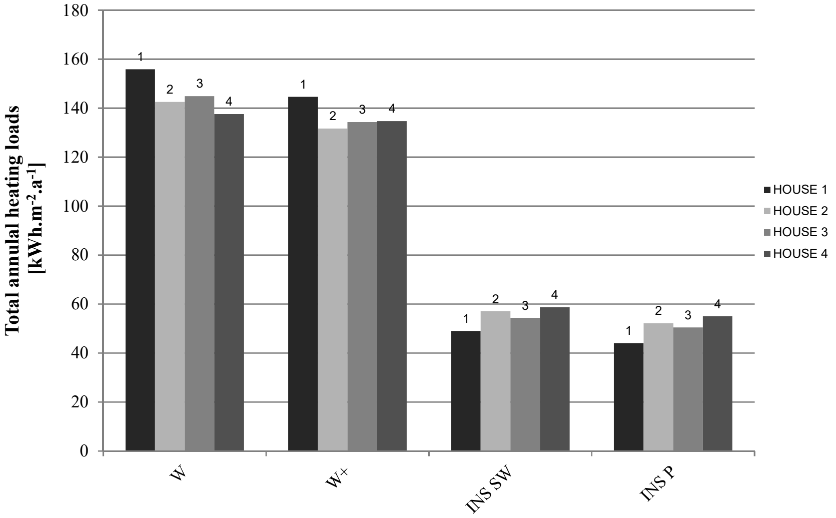

Figure 27 Annual heating demand in the four examined buildings, Cases: W, W+, INS_SW, INS_P

After the weatherization, further enhancing the thermal performance of the houses by fitting them with new windows brings an average improvement of 6% in terms of heating demand reduction. However, in the case of House 4, it can be observed that replacing the old windows with better thermally performing ones brings an improvement of only 3 $kWh.m^{-2}.a^{-1}$ which represents a percentage of 2%. This is due to the fact that House 4 has a very small window surface.

Adding the extra layer of sheep wool insulation brings an average improvement of 60% compared to the weatherization case, and in the case of the polystyrene insulation the improvement is of 62% total annual heating demand reduction. In the weatherization case, House 1 has a considerably higher heating demand, due to the fact that it is the only house to have an unheated basement. However, after insulating the building envelope, the ceiling and especially the basement ceiling, the most noticeable progress was obtained, which is a reduction in heating demand of 66% with sheep wool insulation and 69% with polystyrene insulation, compared to just weatherizing and replacing the windows.

According to the Romanian standards (Law No. 372/2005), all houses are certified with class C performance level after both weatherization and window replacement (with an annual heating demand between 117 and 173 kWh.m^{-2}.a^{-1}). After improving the thermal resistance of the building envelope with either sheep wool or polystyrene, all four examined houses are certified with class A performance level (under 70 kWh.m^{-2}.a^{-1}).

According to European standards (OIB-RL 6 2015), Houses 2, 3 and 4 are certified with class D performance level (between 100 and 150 kWh.m^{-2}.a^{-1}) in both the weatherization and weatherization plus new windows cases, whereas House 1 only falls in this category after having the windows replaced. Before that, in the weatherization case, House 1 certified with class E performance level (between 150 and 200 kWh.m^{-2}.a^{-1}). After having their envelope thermally improved with either sheep wool or polystyrene insulation, Houses 2, 3 and 4 are certified with class C performance level (between 50 and 100 kWh.m^{-2}.a^{-1}) , whereas House 1 is certified with class B performance level (between 25 and 50 kWh.m^{-2}.a^{-1}).

Figures 28 to 31 illustrate the annual heating demand for each of the four examined buildings, in all of the 5 cases.

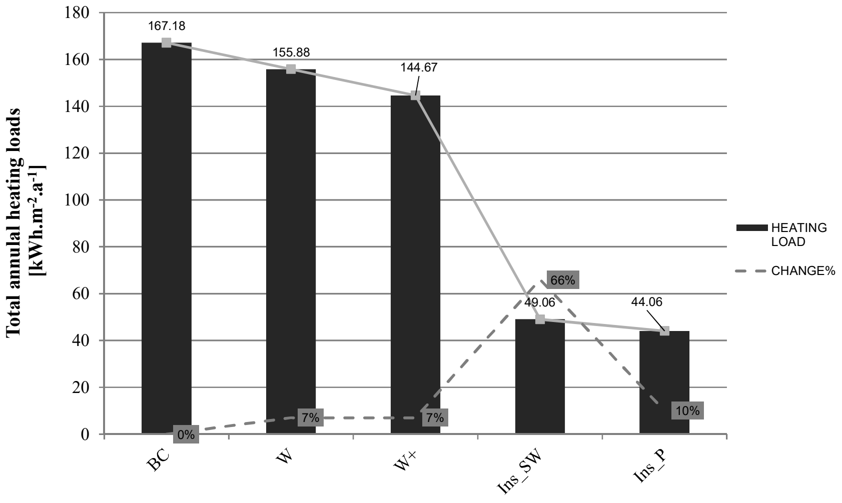

Figure 28 Annual heating demand for House 1, comparison of the 5 cases

As shown in figure 28, weatherization brings an annual heating demand reduction of 7% in House 1, compared to the base case. Even though in the base case the internal loads are slightly different than in the other four cases (as the base case replicates the historic living conditions) and have less of a contribution to indoor air heating, the gross area of the house is also smaller in the base case, as in the other four cases the house was fitted with an extra bathroom. In the base case the air tightness of the houses was simulated by adopting and air change rate value of 0,62h^{-1} (Panzhauser et al. 1992), and in the rest of the cases, in order to show an improvement in air tightness, an air change rate of 0,4 h^{-1} (ONORM B-8110:5 2011) was adopted. Although not an accurate change percentage, it is safe to state that just weatherizing a dwelling brings a noticeable improvement in terms heating demand reduction. Further improving the air tightness by replacing the old windows with thermally efficient ones brings a reduction of 7% in energy consumption. By adding a layer of sheep wool insulation to the building envelope, ceiling and ground floor slab a reduction of 66% was obtained, in comparison to the previous case. In the case where polystyrene was used, another 5 kWh.m^{-2}.a^{-1} could be saved, which means a reduction in energy consumption of 10%, compared to the sheep wool case, and 69% compared to the improved weatherization case. Overall, the sheep wool insulation case shows a 70% improvement and the polystyrene case shows a 73% reduction in energy consumption, compared to the base case.

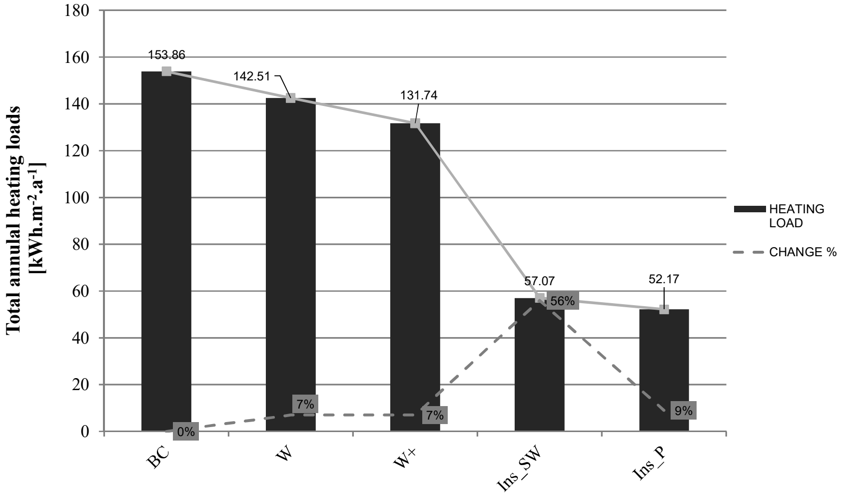

Figure 29 Annual heating demand for House 2, comparison of the 5 cases

Figure 29 illustrates in House 2 an annual heating demand reduction of 7% in the weatherization case in comparison to the base case. However House 2 unlike the other 3 examined houses, was suitable for a bathroom addition in the original perimeter. This means that its gross area remains the same throughout all cases, even though the internal loads increase to meet contemporary living standards. This is the most accurate comparison between the heating demand in the base case and that in the weatherization case, showing that just weatherizing brings a 7% reduction in the annual heating demand.

Further improving the air tightness by replacing the old windows with thermally efficient ones brings a reduction of 7% in energy consumption, compared to just weatherizing. Fitting the building envelope with sheep wool insulation brings in the case of House 2 a 56% reduction in the annual heating demand in comparison to the weatherization with window replacement intervention. Opting for the polystyrene insulation reduces the annual heating demand another 9% in comparison to the sheep wool solution, and 60% compared to the improved weatherization case. Overall, the sheep wool insulation case shows a 62% improvement and the polystyrene case shows a 66% reduction in energy consumption, compared to the base case.

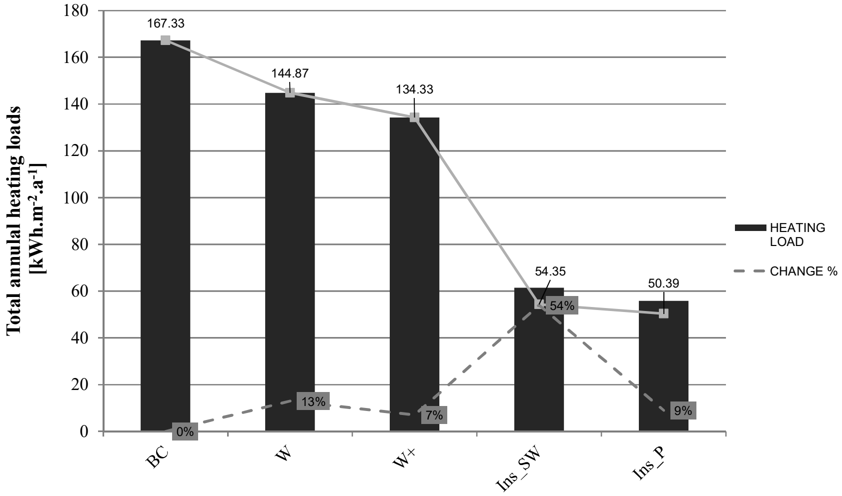

Figure 30 Annual heating demand for House 3, comparison of the 5 cases

Figure 30 illustrates an annual heating demand reduction of 13% that weatherization brings in comparison to the base case. Further improving the air tightness by replacing the old windows with thermally efficient ones brings an improvement of 7% in energy consumption. The results of the next case show that adding a layer of sheep wool insulation to the outside walls, ceiling and ground floor slab brings a reduction in energy consumption of 60% in comparison to the previous case. In the case where polystyrene was used, another 4 kWh.m^{-2}.a^{-1} could be saved, which means a reduction of 7% in energy consumption compared to the sheep wool insulation case and 62% compared to the improved weatherization case. The sheep wool insulation case shows a 67% improvement and the polystyrene case shows a 70% reduction in energy consumption, compared to the base case.

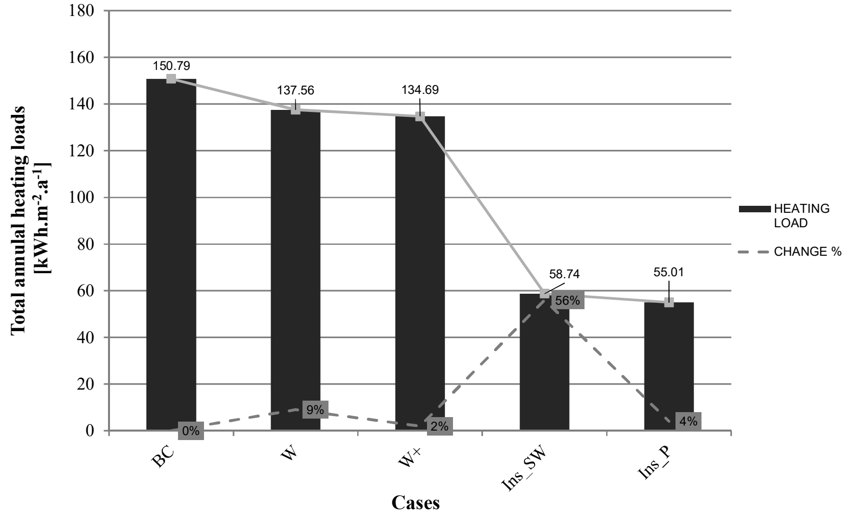

Figure 31 Annual heating demand House 4, comparison of the 5 cases

For House 4, as depicted in figure 31, weatherization brings an annual heating demand reduction of 9%, in comparison to the base case. This is the biggest improvement between these two cases registered in all four houses, and it is due to the fact that House 4 has outside walls made only of wood logs, with no clay layer on the outside, like the other 3 examined houses have. Further improving the air tightness by replacing the old windows with thermally efficient does not have a noticeable impact in this case. The reduction in energy consumption is of only 2%, due to the fact that House 4 has very small windows. By adding a layer of sheep wool insulation to the outside walls, ceiling and ground floor slab, a reduction in heating demand of 56% was achieved, in comparison to the previous case. In the case where polystyrene was used, another 3 kWh.m^{-2}.a^{-1} could be saved, which means a reduction of 4% in energy consumption, compared to the sheep wool case, and a 59% reduction of energy consumption in comparison to the improved weatherization case. The sheep wool insulation case shows a 61% improvement and the polystyrene case shows a 64% reduction in energy consumption, compared to the base case.

5.2 TRANSMISSION LOSSES

Figures 32 to 35 illustrate comparisons of the monthly transmission losses in each of the four examined buildings, in the following cases: W, W+, INS_SW, INS_P.

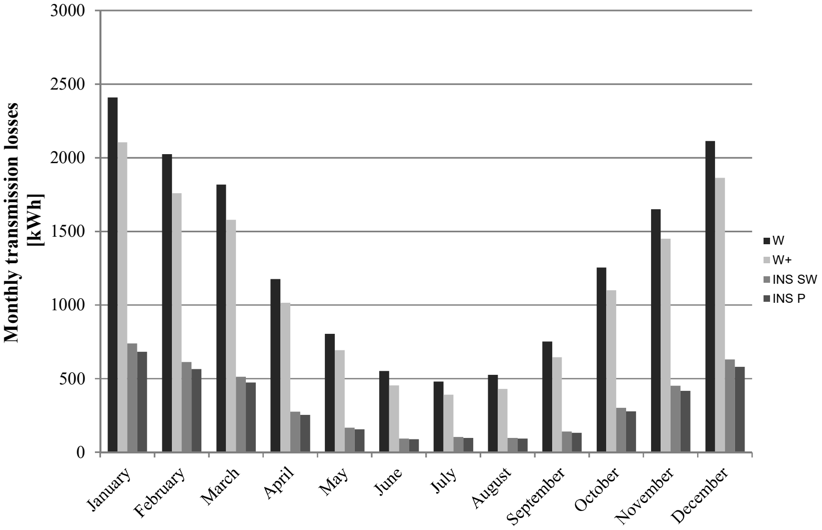

Figure 32 Monthly transmission losses House 1, Cases: W, W+, INS_SW, INS_P

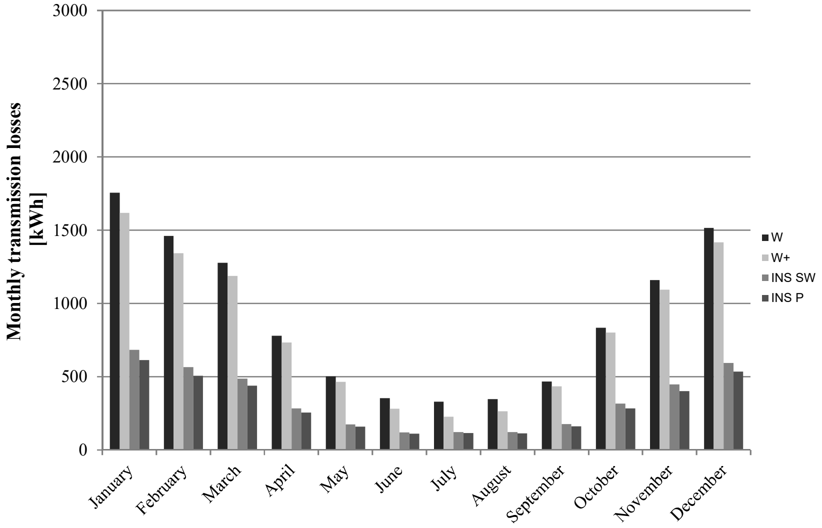

Figure 33 Monthly transmission losses House 2, Cases: W, W+, INS_SW, INS_P

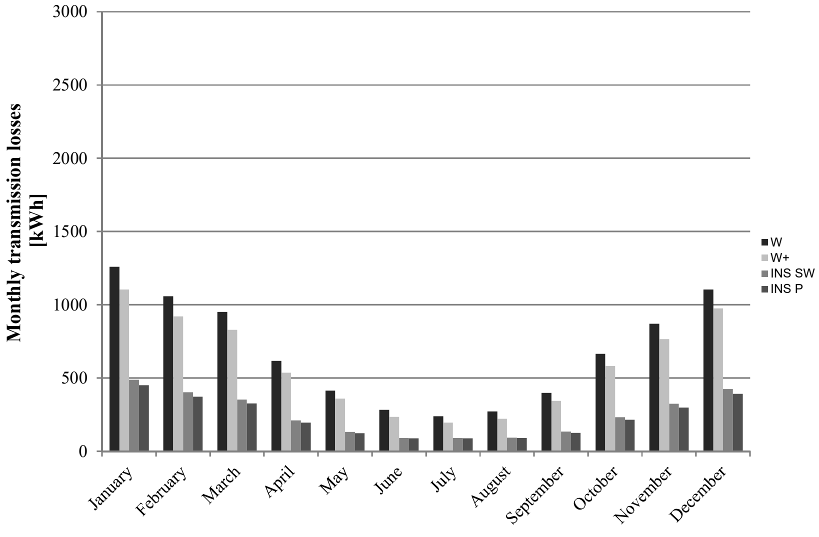

Figure 34 Monthly transmission losses House 3, Cases: W, W+, INS_SW, INS_P

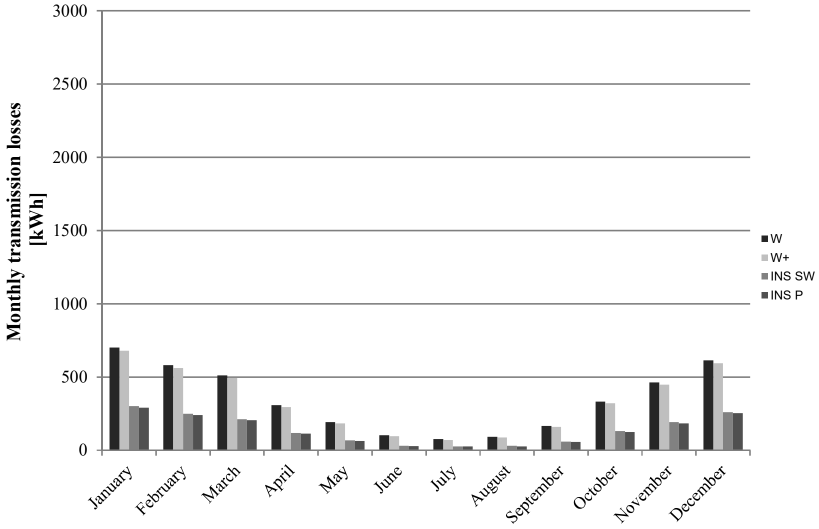

Figure 35 Monthly transmission losses House 4, Cases: W, W+, INS_SW, INS_P

In solid building elements the heat transfer that appears through conduction is due to the temperature difference on either side of the building element. The thermal conductivity, the composition and thickness of layers that constitute the building element are key factors in reducing transmission losses.

Figures 32 to 35 illustrate this by means of the reduced monthly transmission losses during the summer months, when the temperature difference between the inside and outside air is at its lowest. In the case of each of the examined buildings it is visible that opting for thermally performing windows reduces the overall heat loss. Depending on the area of fenestration of each house, the heat losses were reduced in the W+ case as follows: House 1, House 2 and House 3 each register heat loss reduction of 13%, while House 4, due to its small windows, registers an improvement in heat loss reduction of only 4,5%. The average improvement in heat loss reduction brought by improving the window thermal performance of 11%.

The biggest progress is registered while fitting the building envelope with thermal insulation, since the thermally improved surface is much larger. With sheep wool insulation, House 1 shows 70% less heat losses, House 2 and House 3 each show 58% and House 4 shows 57% less heat loss compared to the previous case. With polystyrene insulation, the improvements compared to the weatherization case are as follows: 71% for House 1, 62% for House 2, 61% for House 3 and 59% for House 4. On average, with sheep wool insulation an improvement of 61% was obtained and 63% with polystyrene insulation, compared to the weatherization plus new windows case. This is due to the difference in thermal conductivity of the two materials, which influences the overall U-value of the building elements. The adopted conductivity of sheep wool insulation is 0,038 $W.m^{-1}.K^{-1}$ and that of polystyrene is 0,035 $W.m^{-1}.K^{-1}$. The higher the thermal conductivity is, the higher heat losses occur.

5.3 LOSSES DUE TO AIR CHANGE

Figures 36 to 39 illustrate comparisons of the monthly losses due to air change in each of the four examined buildings, in the following cases: W, W+, INS_SW, INS_P.

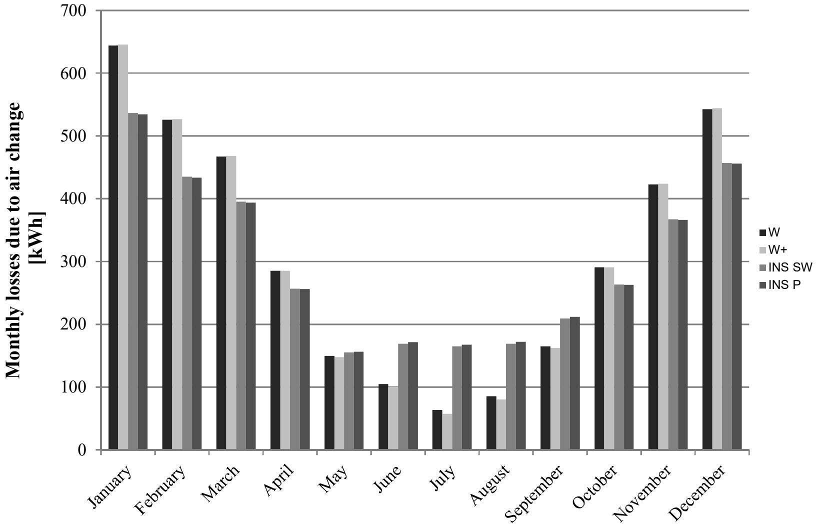

Figure 36 Monthly losses due to air change for House 1 , Cases: W, W+, INS_SW, INS_P

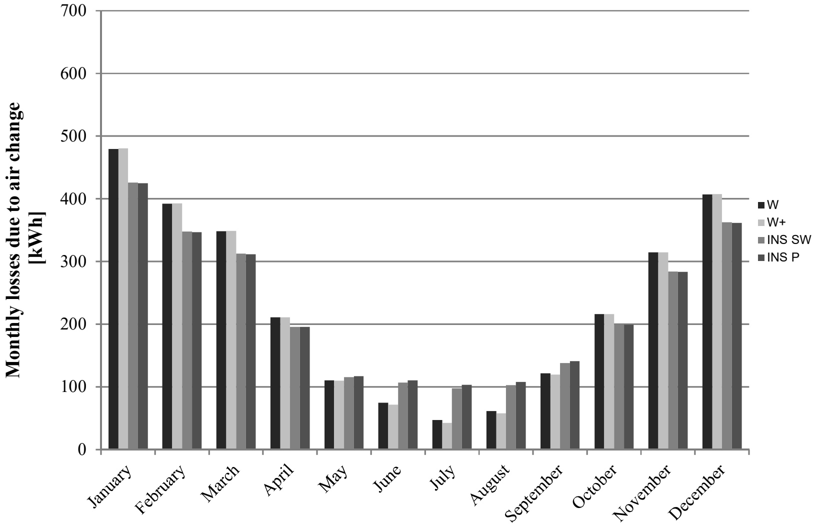

Figure 37 Monthly losses due to air change for House 2 , Cases: W, W+, INS_SW, INS_P

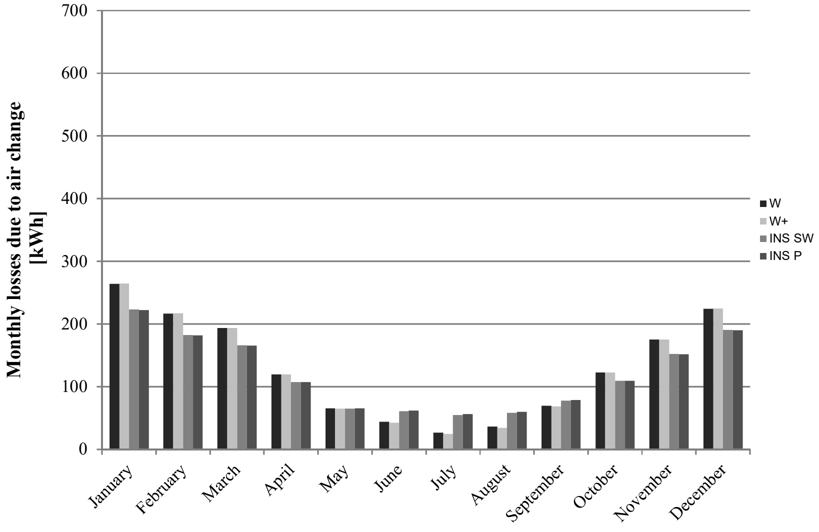

Figure 38 Monthly losses due to air change for House 3 , Cases: W, W+, INS_SW, INS_P

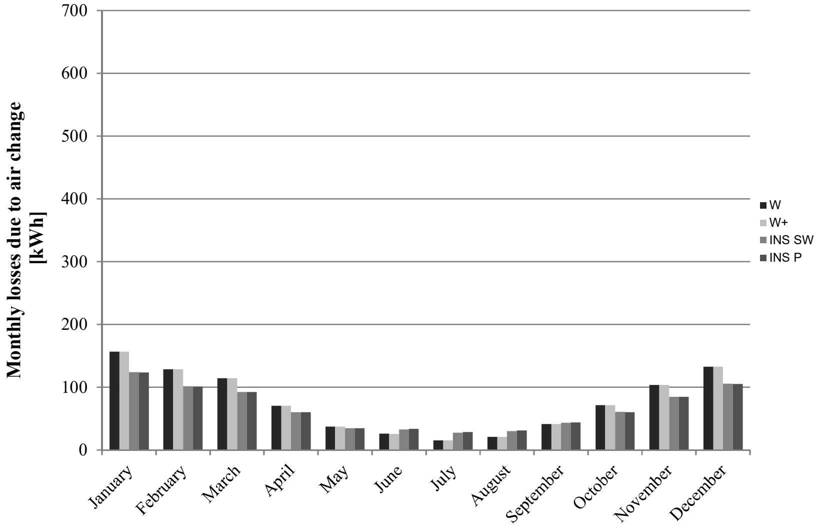

Figure 39 Monthly losses due to air change for House 4 , Cases: W, W+, INS_SW, INS_P

Air infiltration and ventilation in buildings influence both the energy consumption for heating and cooling and the indoor air quality or indoor pollution levels with indoor pollutants (CO_2 and humidity) as well as with urban atmospheric pollutants (resulting from traffic and thermal plants).

Considering the fact that in the simulation the input for the total air change rate is 0,4 h^{-1} (ÖNORM B 8110-5:2011), the total losses due to air change are identical in all the four cases illustrated in figures 36 to 39. The larger houses, House 1 and House 2 have the highest losses due to air change because of their larger volume, 36 $kWh.m^{-2}.a^{-1}$ respectively 34 $kWh.m^{-2}.a^{-1}$, whereas House 3 and House 4 have lower values because of their smaller volume, 27 $kWh.m^{-2}.a^{-1}$ respectively 25 $kWh.m^{-2}.a^{-1}$. However, it is deemed noteworthy the fact that in the last two cases, in which the buildings were fitted with an additional layer of insulation, the distribution of the losses due to air change is more linear and less extreme than in the cases in which the buildings were only weatherized. This shows that thermal insulation has an impact on losses caused by air change, although it alone cannot ensure air tightness.

5.4 SOLAR GAINS

Figures 40 to 43 illustrate comparisons of the monthly solar gains in each of the four examined buildings, in the following cases: W, W+, INS_SW, INS_P.

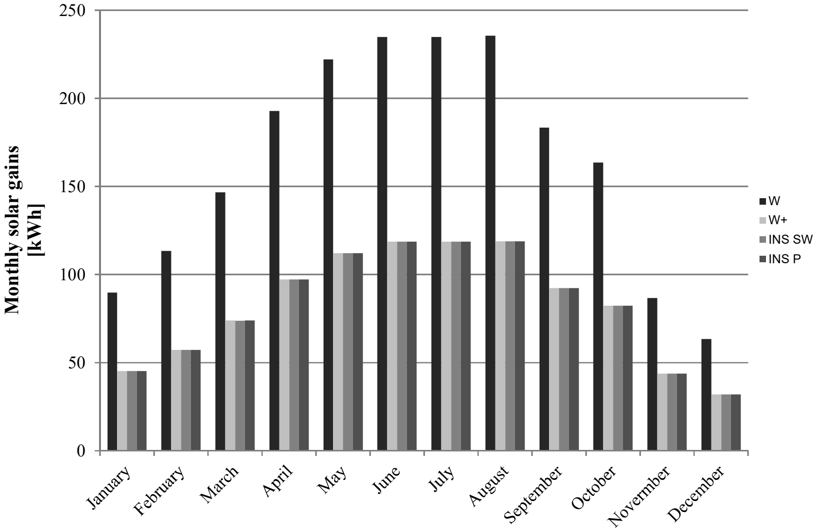

Figure 40 Monthly solar gains for House 1 , Cases: W, W+, INS_SW, INS_P

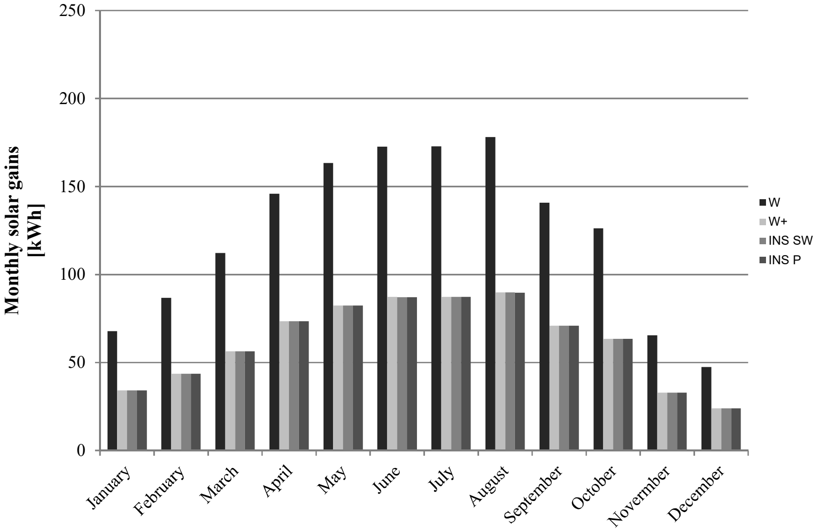

Figure 41 Monthly solar gains for House 2 , Cases: W, W+, INS_SW, INS_P

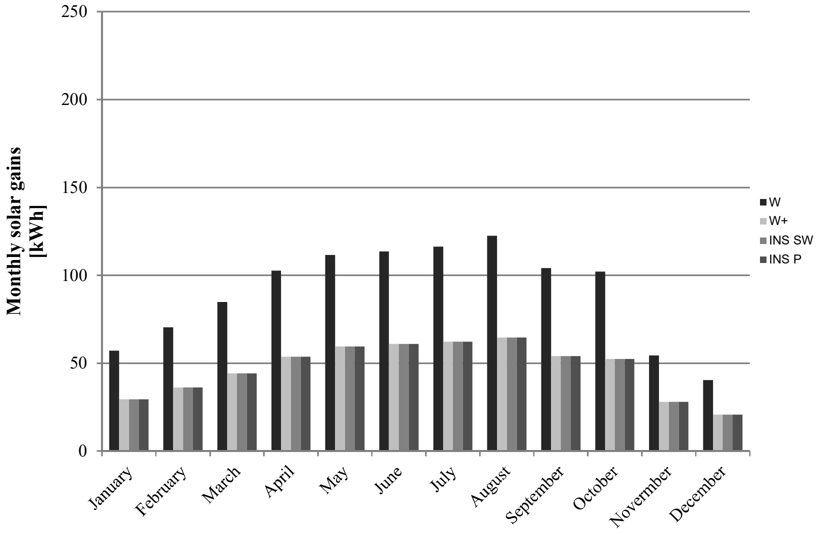

Figure 42 Monthly solar gains for House 3 , Cases: W, W+, INS_SW, INS_P

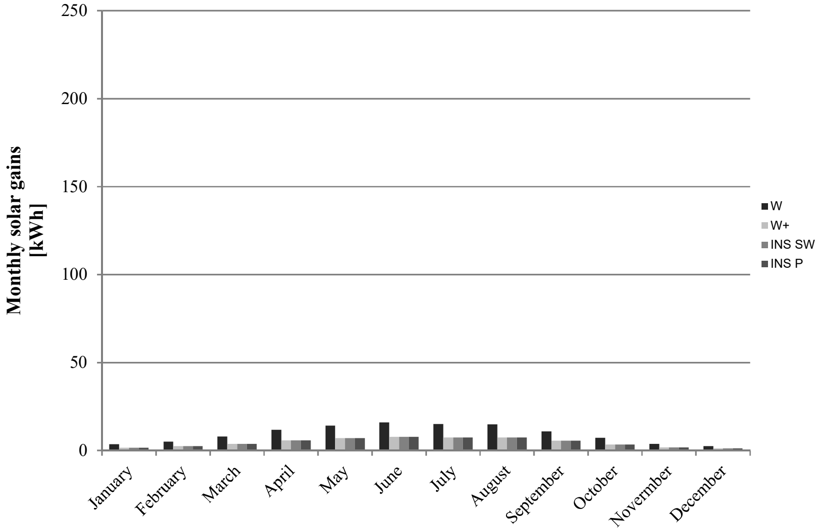

Figure 43 Monthly solar gains for House 4, Cases: W, W+, INS_SW, INS_P

Solar gain is the increase in thermal energy of a space or structure, by means of incident solar radiation absorption.

Solar gains are a welcome contribution to indoor temperatures during the winter time, however during the summer months it can contribute to overheating.

Figures 40 to 43 show that, in the examined buildings, the windows have the biggest impact in solar gain reduction. This is why the major difference in solar gains illustrated by the graphs is from the weatherization case to the weatherization plus thermally improved windows case. As with the previous analyzed parameters, the amount of solar gains largely depends on the size of the building, more precisely on the area of fenestration. In the weatherization case, the solar gains in House 1 are of 20 kWh.m^{-2}.a^{-1}, in House 2 of 19 kWh.m^{-2}.a^{-1}, House 3 has a solar gain value of 20 kWh.m^{-2}.a^{-1} while House 4 only 3,5 kWh.m^{-2}.a^{-1}. However, in the improved weatherization case, the solar gains in House 1 are of 10 kWh.m^{-2}.a^{-1}, in House 2 of 9,5 kWh.m^{-2}.a^{-1}, House 3 has a solar gain value of 11 kWh.m^{-2}.a^{-1} and House 4 of only 2 kWh.m^{-2}.a^{-1}.

The difference in solar gains between the W and W+ case is of 50% each in House 1 and House 2, 45% in House 3 and 43% in House 4. On average, by replacing the single glazed windows with double glazed ones, a reduction in solar gains of 47% was obtained.

As illustrated by the graphs, the highest solar gains are obtained in August, and the lowest values in December.

5.5 INTERNAL GAINS

Figure 44 illustrates the monthly internal gains in each of the four examined buildings, in the following cases: W, W+, INS_SW, INS_P.

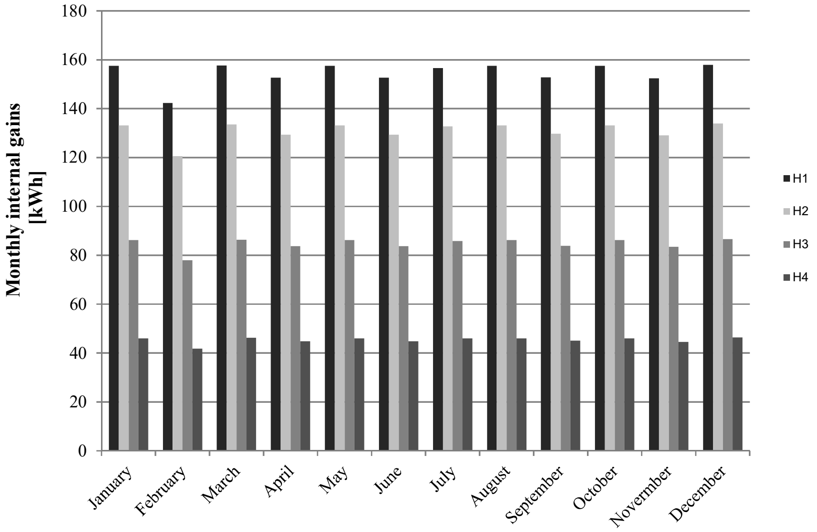

Figure 44 Monthly internal gains for all four houses

According to Table 9, the internal conditions input is identical in each of the four houses, and is consistent throughout all cases. The difference in internal gain values stems from the different gross areas of the analyzed houses, and therefore their particular number of occupants.

The slight variations in internal gain values from one month to another are generated by the fact that odd months have a larger number of days than even ones do.

The total annual internal gain value for House 1 is 1.856 kWh, and the monthly value varies between 142 and 158 kWh, depending on the number of days in the month. The total annual internal gain value for House 2 is 1.572 kWh, and the monthly value varies between 121 and 134 kWh. The total annual internal gain value for House 3 is 1.017 kWh, and the monthly value varies between 78 and 87 kWh, and the total annual internal gain value for House 4 is 544 kWh, and the monthly value varies between 42 and 46 kWh.

5.6 OVERHEATING

Overheating is defined in relation to either thermal comfort, health or productivity. Out of the three, thermal comfort is the design criteria most often considered in the building design process.

As defined by the International Organization for Standardization (ISO), thermal comfort is *"that condition of mind that expresses satisfaction with the thermal environment"* (ISO 7730:2005).

This thermal comfort definition is all encompassing and refers to air temperature, air velocity, mean radiant temperature, relative humidity, clothing insulation and activity level. However, the current state of design parameters of assessing overheating is based *on "the assessment of temperature profiles under typical outdoor temperature conditions, and specifically the frequency, duration and magnitude of temperatures above specified thresholds."*(Mavrogianni et al. 2015).

Overheating has started to become a concern in Europe in the late 1980s, and different countries used different criteria to determine this state. As overheating is in close connection to the climate, and ideally the difference between the indoor and outdoor climate is no higher than 6 to 8 °C (CFCEM 2010), there is still no consensus in terms of what the threshold temperature should be. The extremes are found in the regulations for Bruxelles, where the indoor air temperatures are allowed to be over 25 °C for no more than 5% of the year, and those for the UK, that allow for 1% of the year temperatures of 28 °C in living spaces and 26 °C in bedrooms (Lomas and Porritt 2016).

The Guide for the Calculation of the Thermal Performance of Residential Buildings in Romania recommends using for calculations 25 °C as average indoor air temperature for the summer period (C107/4-2005). However, there is no set temperature as criterion for overheating in the Romanian building regulations.

Therefore, for the simulations, a temperature of 26,5 °C was adopted as overheating threshold, in order to maintain thermal comfort during summer. Furthermore, the indoor air temperature must be kept under 27 °C during the day and under 25 °C at night, according to ÖNORM B 8110-3.

Figures 45 to 48 illustrate the monthly heating loads of House 1, in each of the following cases: W, W+, INS_SW, INS_P.

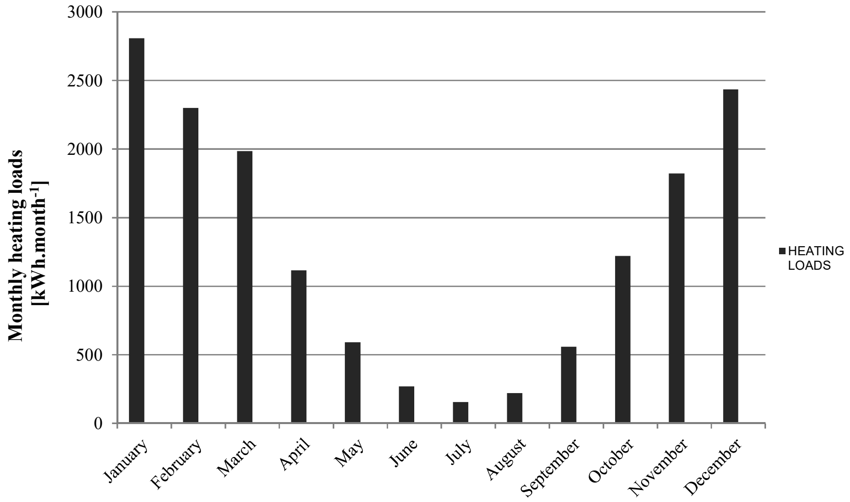

Figure 45 Monthly heating loads of House 1, Case W

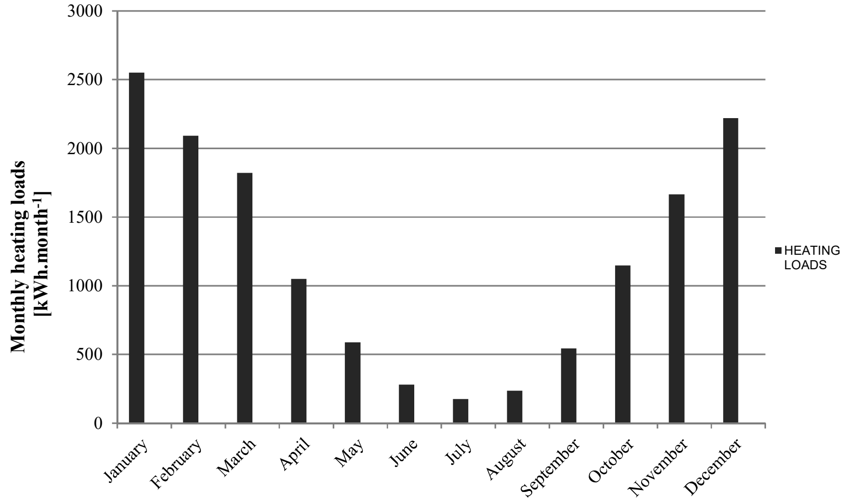

Figure 46 Monthly heating loads of House 1, Case W+

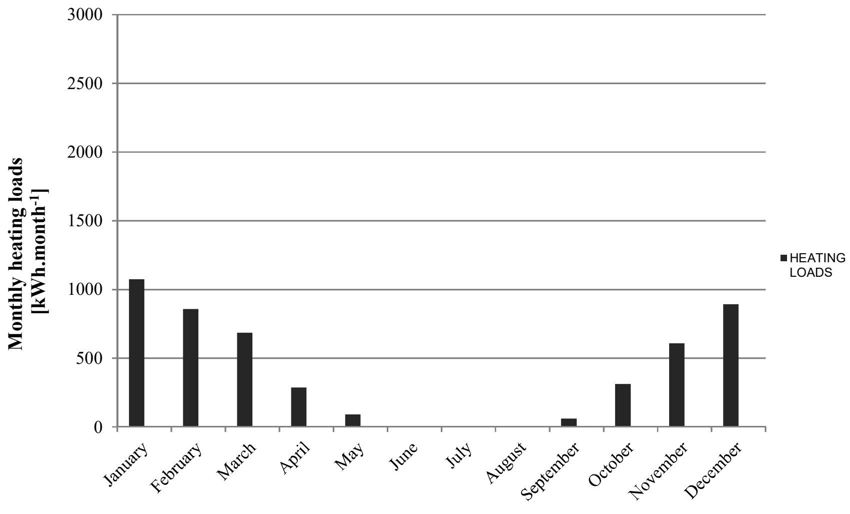

Figure 47 Monthly heating loads of House 1, Case INS_SW

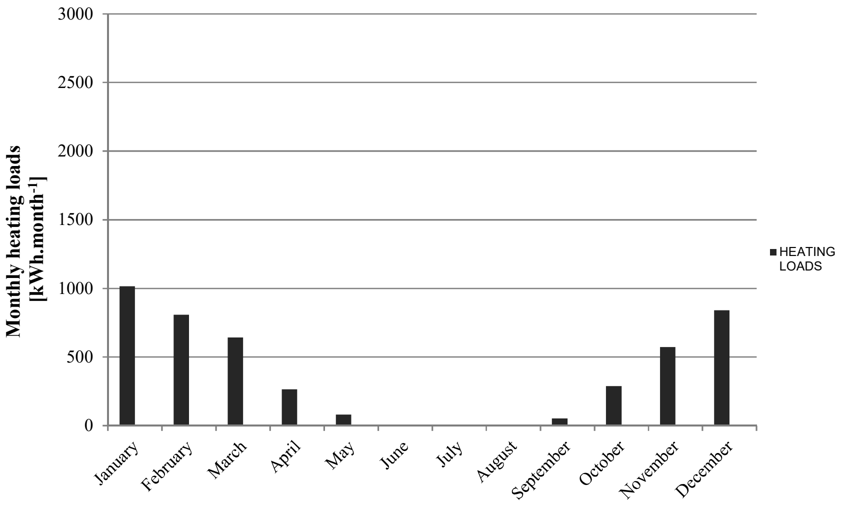

Figure 48 Monthly heating loads of House 1, Case INS_P

As depicted in the graphs, there is no need for cooling in summer in House 1. In the W and W+ cases there is a need for heating throughout the year. The lowest monthly heating demand is of 176 kWh, in the month of July, followed by 238 kWh in September. In the latter cases, INS_SW and INS_P, the months of June, July and August are the months of the year when no heating is required. With sheep wool insulation, the lowest monthly heating load is that of September, which is 61 kWh and is followed by that of May, with 91 kWh.
With polystyrene, the lowest monthly heating load is that of September, which is 54 kWh and is followed by that of May, with 82 kWh. House 1 has the largest

fenestration area, and this shows that, in this case, the solar gain is a welcome addition to the indoor air temperature.

Figures 49 to 52 illustrate the monthly heating loads of House 2, in each of the following cases: W, W+, INS_SW, INS_P.

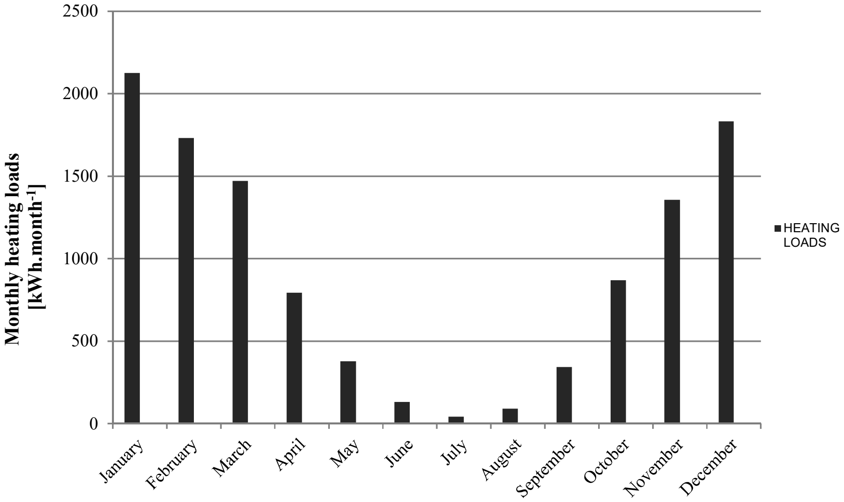

Figure 49 Monthly heating loads of House 2, Case W

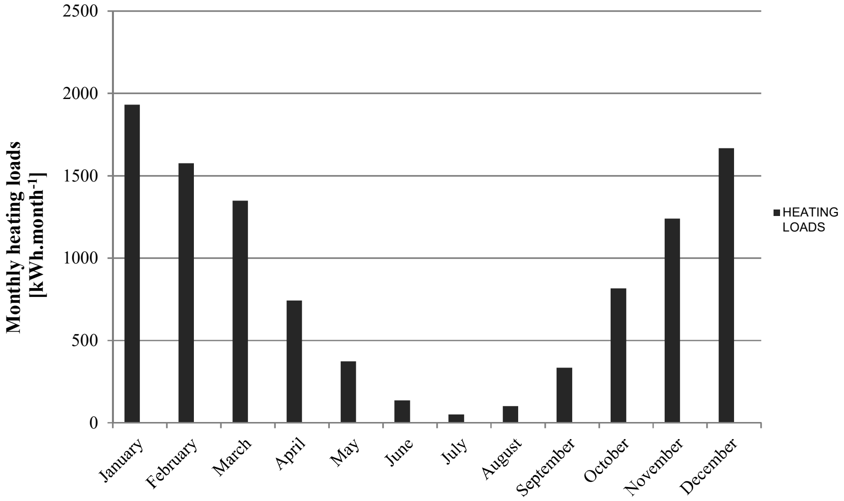

Figure 50 Monthly heating loads of House 2, Case W+

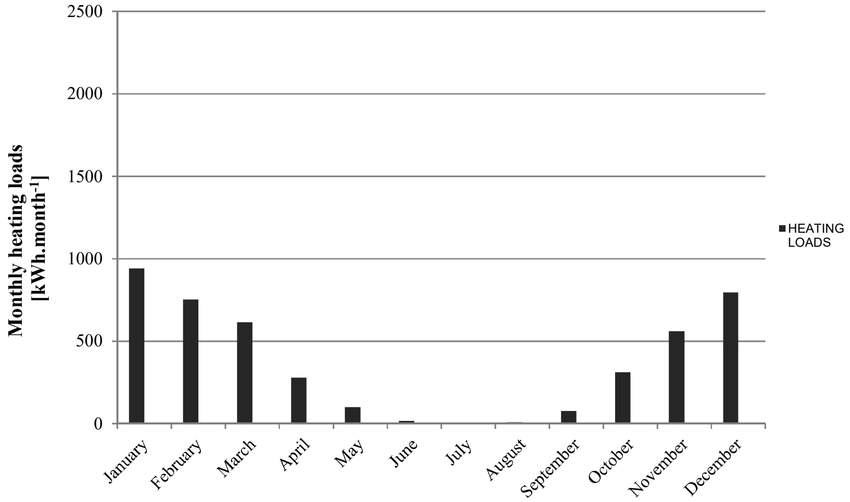

Figure 51 Monthly heating loads of House 2, Case INS_SW

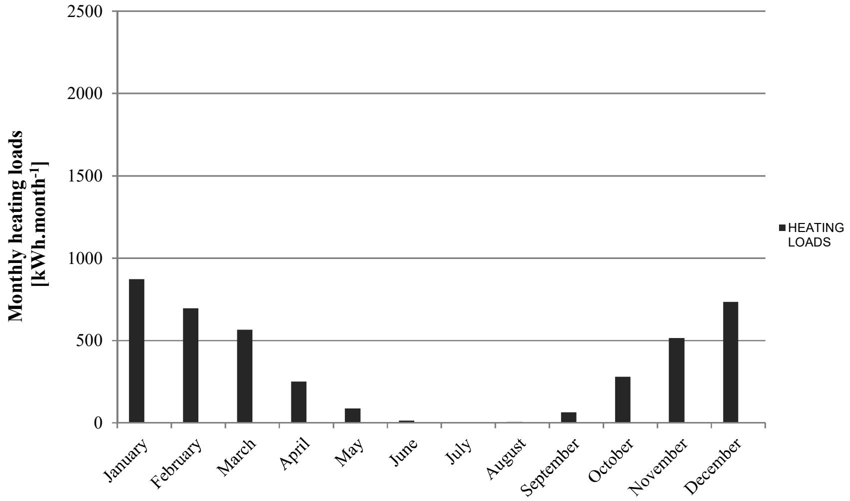

Figure 52 Monthly heating loads of House 2, Case INS_P

In the case of House 2, there is no need for cooling in summer. In the W and W+ cases there is a requirement for heating, even in the summer months. The lowest monthly heating demand is of 52 kWh, in the month of July, followed by 101 kWh in September. In the second and third case, INS_SW and INS_P, the months of June, July and August are the months of the year when no heating is required. With sheep wool insulation, the lowest monthly heating load is that of September, 79 kWh and is followed by that of May, with 102 kWh. With polystyrene insulation, the lowest monthly heating load is that of September, 65kWh and is followed by that of May, with 87 kWh.

Figures 53 to 56 illustrate the monthly heating loads of House 3, in each of the following cases: W, W+, INS_SW, INS_P.

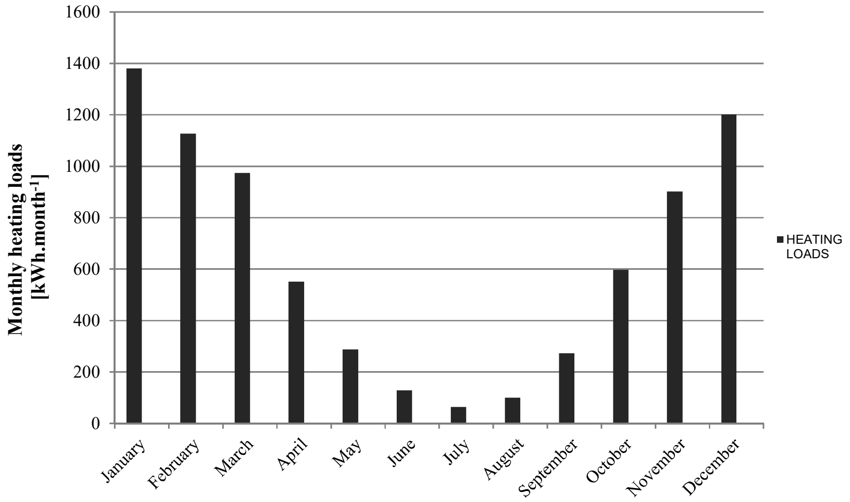

Figure 53 Monthly heating loads of House 3, Case W

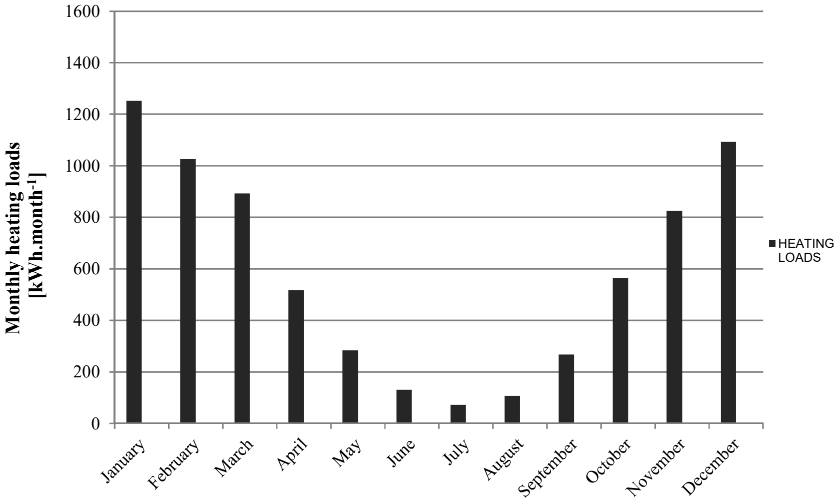

Figure 54 Monthly heating loads of House 3, Case W+

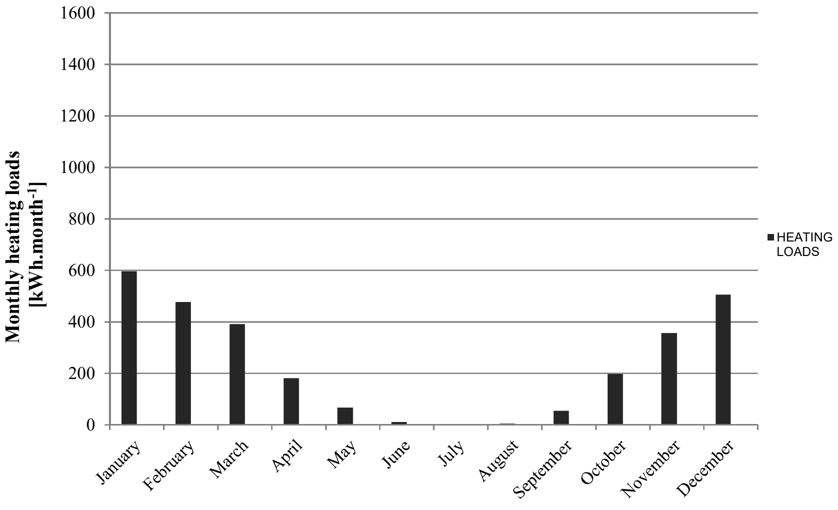

Figure 55 Monthly heating loads of House 3, Case INS_SW

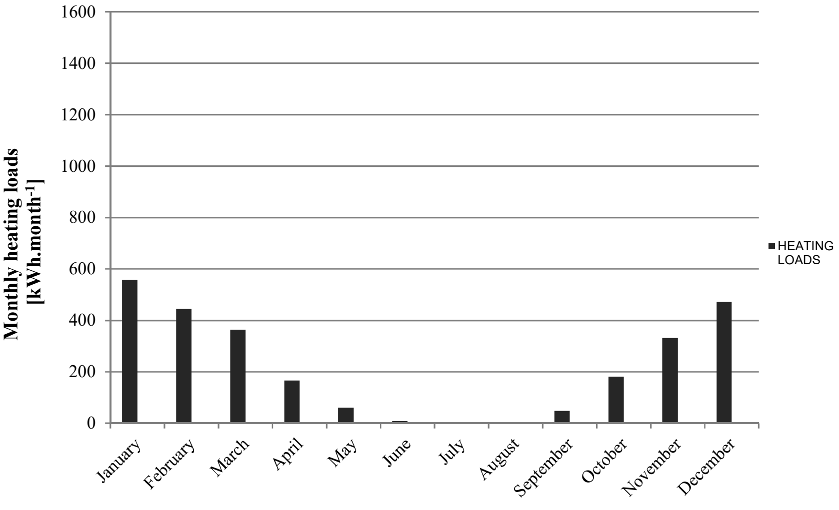

Figure 56 Monthly heating loads of House 3, Case INS_P

House 3 also has no requirement for cooling in summer. In the W and W+ cases there is a need for heating throughout the year. The lowest monthly heating demand is of 72 kWh, in the month of July, followed by 106 kWh in September. In the other two cases, INS_SW and INS_P, June, July and August are the months of the year when no heating is required. With sheep wool insulation, the lowest monthly heating load is that of 54 kWh in September, followed by that of 67 kWh in May. With polystyrene insulation the lowest monthly heating load is that of 48 kWh in September, followed by that of 60 kWh in May.

Figures 57 to 60 illustrate the monthly heating loads of House 4, in each of the following cases: W, W+, INS_SW, INS_P.

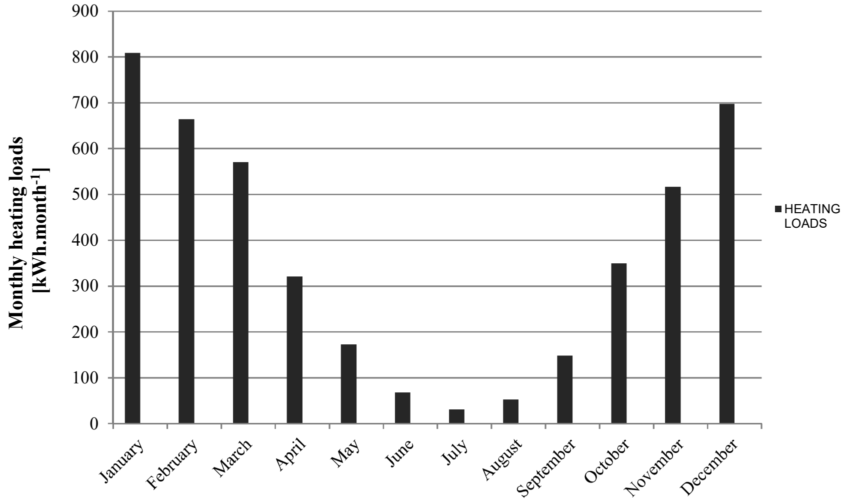

Figure 57 Monthly heating loads of House 4, Case W

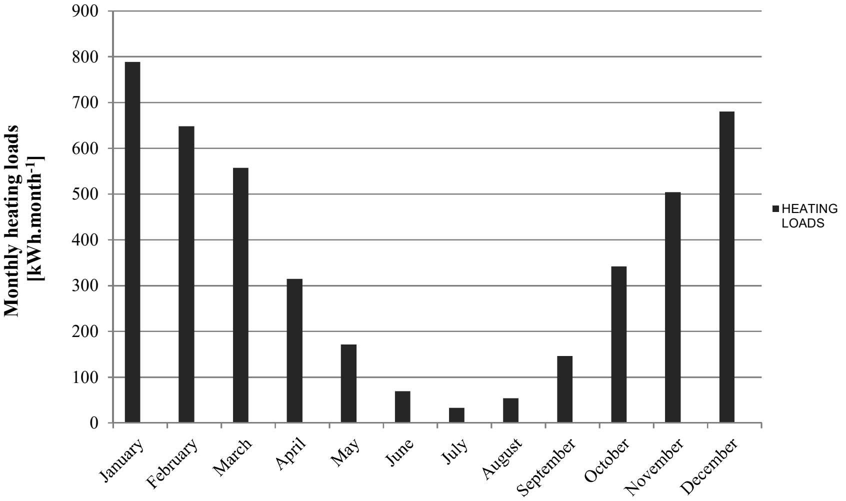

Figure 58 Monthly heating loads of House 4, Case W+

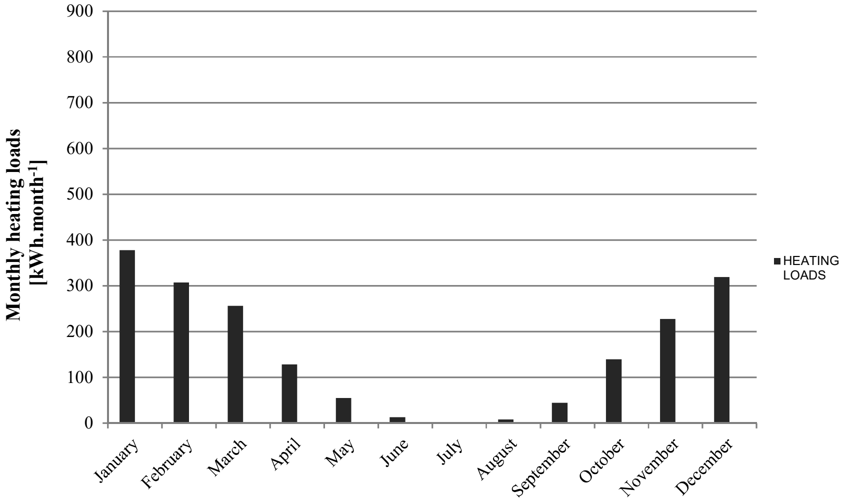

Figure 59 Monthly heating loads of House 4, Case INS_SW

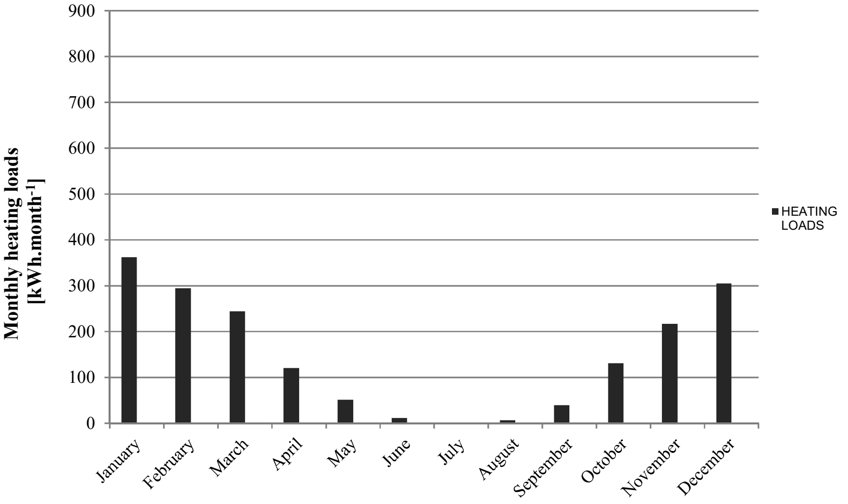

Figure 60 Monthly heating loads of House 4, Case INS_P

As in the case of all the other examined houses, there is no need for cooling in summer in House 4 either. In the first two cases there is a need for heating throughout the year. The lowest monthly heating demand is of 31 kWh, in the month of July. In the latter cases, July is the only month of the year when no heating is required. With sheep wool insulation, the lowest monthly heating load is that of August, with 8 kWh followed by that of June, with 13 kWh. With polystyrene, the minimum heating loads are 6 kWh in August followed by 11 kWh in June. This is partly due to the small fenestration area of House 4, which does not allow for much solar gain, which the indoor climate of this house could have benefited from.

5.7 LIFE CYCLE ANALYSIS COMPARISON – SHEEP WOOL INSULATION VS. POLYSTYRENE INSULATION

Below, Figure 61 compares the annual heating demand in each of the four examined buildings, in the following cases: INS_SW, INS_P.

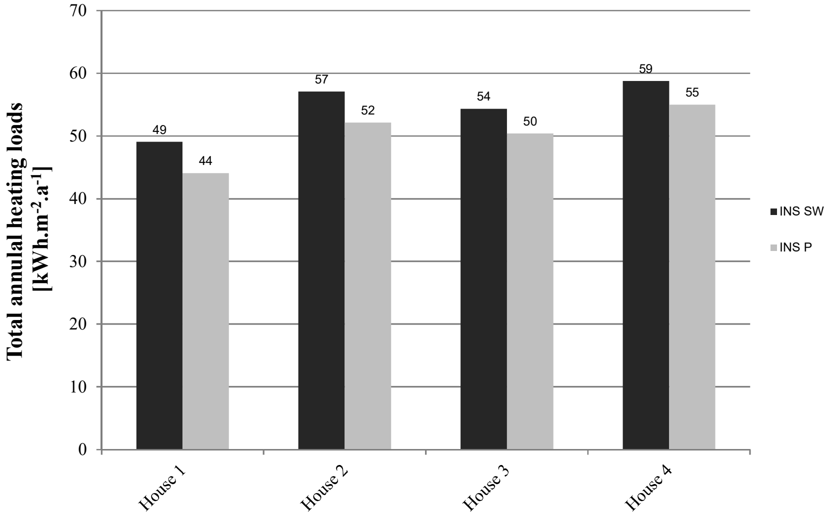

Figure 61 Annual heating demand in all four houses, in the following cases: INS_SW, INS_P.

Even though using the expanded polystyrene insulation brought an average reduction of 8% in heat consumption, there are several other factors to consider before declaring it the best choice.

Making a Life Cycle Assessment comparison can determine whether the sheep wool insulation presents enough advantages to make up for the slightly higher thermal conductivity.

A Life Cycle Assessment (LCA) is an evaluation of the inputs, outputs and environmental impact that a products has during its life cycle. The LCA contains four steps which investigate the impact of the raw material production, manufacturing, use and maintenance and the disposal of the product at the end of its use. Each of these four steps should be divided into four categories, according to the MECO principle. MECO stands for material, energy, chemicals and other issues, and is a principle which divides the assessment into four areas corresponding to the main underlying factors that cause products to impact the environment.(Korjenic et al. 2015)

Thermal insulation materials fall into one of the following categories: inorganic materials, organic materials, combined materials and new technology materials (Papadopoulos 2005).

Both sheep wool insulation and expanded polystyrene (EPS) belong to the organic materials category, however EPS is derived from a petrochemical feedstock and is therefore a polymer, whereas sheep wool is bio-based and thus renewable (Duijve 2012).

Table 14 Properties of the insulation products adopted in the simulation

Product	**Producer**	**λ [W.m^{-1}.K^{-1}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**	**Thickness [mm]**	**Cost [€/ m²]**
Isolena OPI 18	ISOLENA	0.0385	1760	80	14.66
Styropor EPS 035	STYROPOR	0.0350	1500	80	7.25

5.7.1 Life Cycle Analysis of Sheep wool thermal insulation

According to Korjenic et al., the LCA of sheep wool insulation can be assessed as described in the following points:

5.7.1.1 RAW MATERIAL ACQUIREMENT STAGE

Material

Sheep wool is a natural, renewable material and a byproduct of sheep farming. Sheep grow their wool constantly, and they get uncomfortable if not sheared once a year. It takes a professional shearer roughly 5 minutes to shear a sheep.

Energy

Some farmers use scissors, while others use special machinery to shear sheep wool. Therefore the energy required is relatively low, though labor intensive.

Chemicals

Since the dirty wool consists of 60% wool and 40% of sweat, excrement, dirt and grease, it must be accordingly washed. However, due to the fact that sheep wool only recently started being used as an insulation material on a larger scale, not every country is equipped with a complete wool processing facility. Bukovina does not yet have a production facility of sheep wool insulation, therefore the panels have to be imported from Austria. However, Austrian companies such as Daemwool also send the wool to Belgium to be washed and impregnated with moth protection (Thorlan IW), after which it is brought back for processing. (Daemwool 2018) This which adds extra transport-ways and creates further CO_2 emissions.

Other

Another byproduct of sheep farming is manure. Even though not harmful to the environment, it still needs to be disposed of. A sheep farm with 100 heads can produce up to 50 tons of manure. This can be transformed in compost and distributed. Also, sheared sheep may require more feed.

5.7.1.2 PRODUCTION STAGE

Material

The impact on the environment varies depending on the facility, location and infrastructure.

Energy

The production of sheep wool insulation requires less than 15% energy when compared to glass wool insulation. This is due to the fact that sheep wool insulation is made from a natural fiber. Material collection is performed manually and requires very little energy. At the moment however, there are no production facilities in Romania for the manufacturing of sheep wool insulation panels. Thus, after the manual shearing, the wool has to be transported to the nearest production plant in Austria for the production process, leading to energy consumption and CO_2 emissions.

Chemicals

The wool requires washing, in order to remove dust and impurities. To avoid water contamination, only an eco-friendly soap should be used.

Other

Lanolin is a byproduct of sheep wool processing. It is a natural substance secreted by the sebaceous glands of the sheep, and is commercially used in a wide range of products. However, if there is no company that produces lanolin in the country, it needs to be disposed of.

5.7.1.3 PACKAGING AND DISTRIBUTION STAGE

Material

In this stage, the highest environmental impact is presented by the fuel consumed to transport the sheep wool to the insulation panel manufacturing facilities. Currently sheep wool insulation panels are not being produced in Romania.

Energy

Wool is not a dense material and occupies a lot of space. More compact bales would have a decreased volume and lead to a decrease in transportation costs.

Chemicals

Considering the fact that the wool needs to be transported to another country in order for the panel to be produces, the environmental impact of the chemicals released during transportation is high, including the highest ratio of GWP, smog, ozone layer depletion, depletion of minerals and fossil fuels.

5.7.1.4 USE AND MAINTENANCE STAGE

Material

Sheep wool has no negative impact on human or animal health. Moreover, it has been proven to absorb and break down indoor air pollutants such as nitrogen dioxide, sulphur dioxide and formaldehyde and thus improve indoor air quality.

Energy

Using sheep wool thermal insulation, dwellings can save up to 80% energy by having a reduced demand for heating and cooling.

Chemicals

No special equipment is required while handling the sheep wool insulation. It is safe to touch and breathing in its vicinity presents no health risk.

Other

Not only does sheep wool insulation not present any hazards to human health, but it has several advantages. Due to hygroscopic abilities, it can absorb and desorb moisture without having its insulating capabilities reduced. In case of a fire, wool will extinguish itself, as it does not support combustion. It absorbs and thus reduces noise levels. Sheep wool does not collect static energy, and because of that is also does not attract lint and dust from the air.

5.7.1.5 DISPOSAL STAGE

Material

Sheep wool has no impact on the environment. When no longer used, the wool from the insulation panels can be repurposed or biodegraded in nature.

Energy

The energy that goes into repurposing the wool is considerably less that the one it went into processing the raw wool, since many of the steps like shearing, combing and washing are only necessary once.

Chemicals

Sheep wool is to be repurposed or biodegraded. However, if disposed of inappropriately by incineration, the fumes released can be damaging to the environment.

5.7.2 Life Cycle Analysis of polystyrene thermal insulation

5.7.2.1 RAW MATERIAL ACQUIREMENT STAGE

Material

EPS is produced from the monomer “monotsyrene”, which is derived from benzene and ethylene, both non-renewable petroleum products. (Duijve 2012)

Energy

Monostyrene gets polymerized with pentane (blowing agent) and Hexabromocyclododecane (fire retardant) in order to form the polystyrene granulate also called polystyrene beads. Steam is then applied, in order to heat the pentane that causes the beads to expand. A cell structure is thus created within the beads, in which the pentane is replaced with air. After this step, the polystyrene beads are called “pearls”. The polystyrene pearls are cooled down and stored into silos (Duijve 2012) This is the primary material out of which the thermal insulation boards are made.

Chemicals

In the Fourteenth report on Carcinogens, the US Department of Health and Human Services lists Styrene under the category of substances “Reasonably Anticipated to be Human Carcinogens”. It is stated in the report that *“a causal relationship between styrene exposure and cancer in humans is credible and is supported by the finding of DNA adducts and chromosomal aberrations in lymphocytes from styrene-exposed workers.”*

5.7.2.2 PRODUCTION STAGE

Material

EPS has an extremely low density and weight. Because it is up to 98% air, it is as little as 2% plastic, meaning its contribution to plastic production compared to its volume is very low.

Energy

To produce the thermal insulation panels, the pearls are once again heated and pressed into the desired shape. (Duijve 2012)

Chemicals

In 2010, the US Environmental Protection Agency (HHS) has released the “HCDB Action Plan” in which the following information was published ***“****Human exposure is evidenced from its presence in breast milk, adipose tissue and blood. It bioaccumulates and biomagnifies in the food chain. It persists and is transported long distances in the environment, and highly toxic to aquatic organisms. It also presents potential human health concerns based on animal test results indicating potential reproductive, developmental and neurological effects. For these reasons, the Environmental Protection Agency (EPA) intends to consider initiating action under the Toxic Substances Control Act to address the manufacturing, processing, distribution in commerce, and use of HBCD.* ***”***

5.7.2.3 PACKAGING AND DISTRIBUTION STAGE

Material

As with sheep wool insulation, polystyrene boards are bulky due to their low density, and take up a lot of space when distributed.

Energy

However, due to the ubiquity of factories that produce this material, the effects on the environment that its transportation causes are quite low.

Chemicals

Low environmental impact caused by transportation.

5.7.2.4 USE AND MAINTENANCE STAGE

Material

If not treated with a flame retardant, polystyrene is highly flammable. When polystyrene is burning, carbon monoxide and styrene monomers are released into the atmosphere, which are hazardous to human and animal health. (HHS 2011) *"According to the European Chemicals Agency (ECHA) there are currently no commercially or technically viable alternatives for HBCD as a flame retardant in polystyrene foam, as all alternative flame retardants it noted impair the structure and properties of the foam, making it unsuitable for use"* (ECHA 2009).

Energy

The thermal conductivity of polystyrene is even lower than that of sheep wool. This means that strictly from a thermal insulation point of view, EPS performs very well.

Chemicals

In the event of a fire, the fumes released by the burning polystyrene in the atmosphere and in the indoor environment are damaging to human and animal health and to the environment.

Others

In our particular example, where the insulation was placed on the inner face of the outside wall, there is a risk for mildew to develop. A way to avoid this from happening is to ensure that the polystyrene board is properly ventilated on both sides. This, however, brings the disadvantage of further reducing the net area of the insulated building.

5.7.2.5 DISPOSAL STAGE

Material

Although polystyrene is recyclable, currently a large portion is disposed of in landfill. The way it was mounted plays a decisive role, as once the EPS has been glued to a construction, the disposal of this composite element proves to be difficult.

The study „Dismantling, recycling and recovery of thermal insulation systems" it is sated that there are several options for the selective dismantling of thermal insulation systems. A generally preferable recommendation for action is not given in the study, but the extensive documentation of the investigations facilitates the decision for a suitable method on the actual object.

A common reason for decommissioning is the fact that older thermal insulation systems no longer meet current requirements. In the sense of waste prevention, the "doubling up" is recommended in this case: the existing thermal insulation is not dismantled but reinforced by an additional insulating layer. The useful life of the thermal insulation systems could thus be extended to a period of 40 be extended for up to 120 years. The prevention of waste has the highest priority, old thermal insulation systems do not necessarily have to be dismantled.

Care and maintenance significantly increase the service life of thermal insulation systems. Due to increasing thermal requirements, existing systems can be doubled. This avoids waste. If a thermal insulation system needs not be dismantled, then no disposal problems are to be expected in the long term. (Albrecht und Schwitalla 2015)

The Expanded Polystyrene Association of Southern Africa presents the positive aspects of this happening, such as*: "EPS waste is inert and non-toxic, so the landfill site becomes more stable. EPS aerates the soil, encouraging plant growth or reclaimed sites."* However, the fact that discarded polystyrene is resistant to photo-oxidation and does not biodegrade for over 500 years is not to be ignored.

Energy

There are several ways polystyrene can be recycled. The most beneficial way is by direct re-use: the clean EPS waste goes through a grinding process, after which it is added to the production of new products, together with virgin material.

Another way is to have it melted and then extruded, in order to make compact polystyrene. This new material can be used for items such a plant pots, coat hangers or as a wood substitute.

Polystyrene pearls can also be used as aggregate for lightweight concrete, for both its structural and thermal insulating capabilities. (EPSASA 2006)

Chemicals

"The frequent detection of HBCD over a large geographic area, with increasing exposure in remote locations such as the Arctic, where no demonstrable local sources exist that can account for these exposures, suggest that HBCD is persistent and undergoes long-range atmospheric transport" (UNEP 2007).

Table 15 Life Cycle Analysis (CTGr) comparison between sheep wool insulation and polystyrene

LCA - CTGr					
STAGE	**MECO**	**Sheep Wool**	**Sc**	**EPS**	**Sc**
Raw material acquirement	**Materials**	Natural, renewable, sustainable	10	Oil-based, non-renewable	1
	Energy	Manual shearing – low energy, labor intensive	9	4 step production process	2
	Chemicals	Wool washing in a different country implies CO_2 emissions due to extra transport-ways	7	Styrene monomer presents health hazards and is a carcinogen	1
	Other	100 sheep produce 50 tons of manure	9	-	10
Production	**Materials**	Depending on the facility and infrastructure	7	It is up to 98% air, and as little as 2% plastic	9
	Energy	After shearing, the wool needs to be sent to Austria for processing – CO_2 emissions	9	Additional step: heat and pressure melt the beads into desired shape	3
	Chemicals	The soap used can lead to chemical water and soil contamination	7	HBCD presents health hazards	1
	Other	Lanolin is a byproduct	8	-	10

LCA - CTGr					
STAGE	**MECO**	**Sheep Wool**	**Sc**	**EPS**	**Sc**
Packaging and distribution	**Materials**	Not yet produced in Romania – Transportation from factory to construction site	1	It is also produced in Romania – easily available	10
	Energy	Bulky – takes up a lot of space	3	Bulky – takes up a lot of space	3
	Chemicals	Not yet produced in Romania – import from Austria	1	Produced everywhere – low CO_2 emission from transportation	10
Use and maintenance	**Materials**	Absorbs and breaks down indoor air pollutants	10	It is flammable, When treated it is toxic	1
	Energy	Homes can save up to 80% on energy	10	Even lower thermal conductivity	10
	Chemicals	It is safe and easy to handle – no special equipment required	10	If burning, the released fumes are toxic	1
	Other	Presents no hazards to human health	9	Mildew if not ventilated Smaller net area of building	1
Disposal	**Materials**	It is biodegradable and can be remanufactured	4	It is recyclable, but under certain conditions	6
	Energy	Low energy required to remanufacture	9	Gets melted and remolded for packaging	9
	Chemicals	If incinerated, the fumes can damage the environment	1	If sent to landfill, its chemicals contaminate water and soil	1
TOTAL SCORE		**Sheep wool**	**124**	**EPS**	**90**

In the figures 62 and 63 Asdrubaldi el al. show that the sheep wool thermal insulation clearly has the least impact over the environment in terms of embedded energy and global warming potential (GWP).

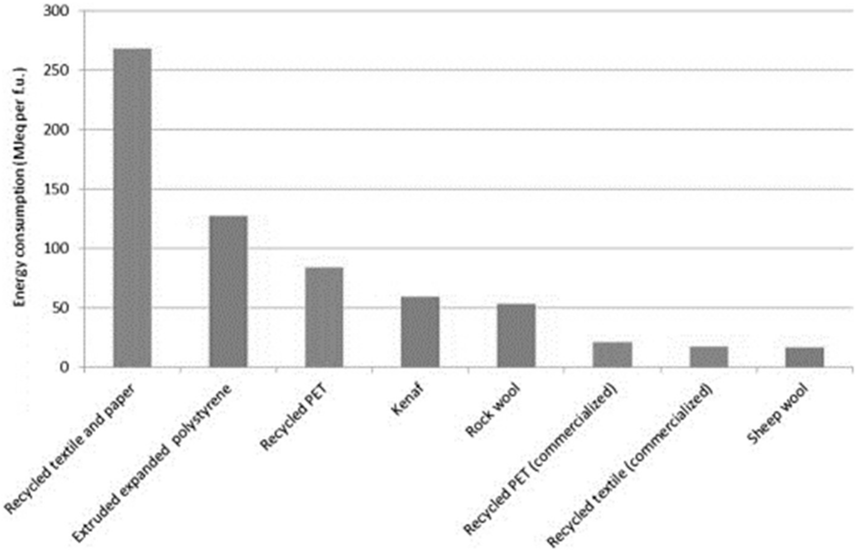

Figure 62 Embodied energy, in terms of MJeq per functional unit, of thermal insulation materials (Source: Asdrubaldi et al. 2015)

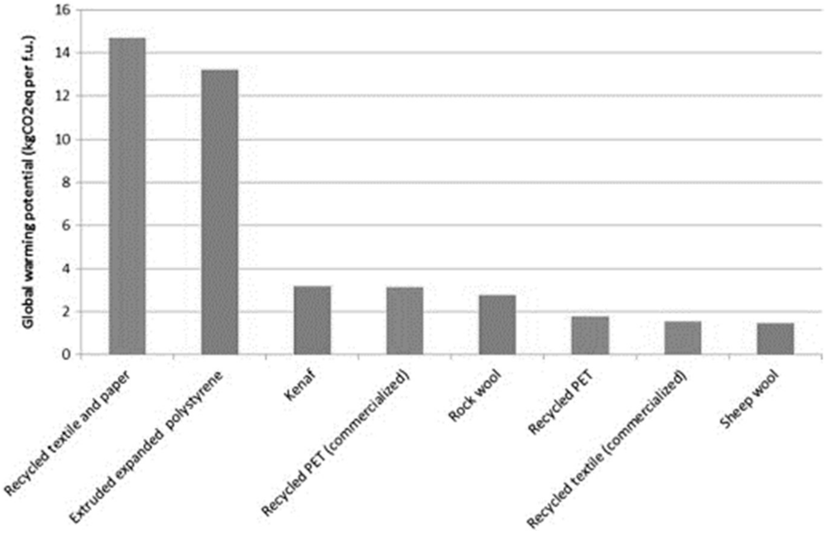

Figure 63 Global warming potential, in terms of kgCO$_2$eq per functional unit, of thermal insulation materials (Source: Asdrubaldi et al. 2015)

It has been shown that, even though not as popular, the thermal performance of sheep wool insulation is comparable to that of polystyrene. Considering the many other advantages in terms of low impact on the environment and no impact on human health, sheep wool insulation should be more often considered as a thermal insulation solution not only for renovations and but for new buildings as well.

6. Conclusion

6.1. ON THE FEASIBILITY OF CONTINUING USING THE OLD BUILDINGS

This study focuses on the thermal assessment of four houses belonging to the vernacular architecture from Bukovina, Romania. Dynamic thermal simulations were carried out with help of the EDSL Tas software in order to investigate the performance of the examined buildings in terms of annual heating loads and whether overheating should be a concern during the summer months.

Five different scenarios were simulated, in order to assess the thermal response of the buildings. The first scenario simulates the buildings in the state that they currently are, with an air change rate of $0,62h^{-1}$. In the second scenario, the building air change rate was changed to 0,4 $h^{-1,}$ in order to get the thermal response of weatherized buildings, yet the original windows were not changed. The third scenario is replacing the old windows with thermally efficient ones, together with the weatherization of the houses. In the fourth and fifth scenarios, the building envelope U-values were improved by adding a layer of thermal insulation of sheep wool, respectively polystyrene.

The two thermal insulation materials were chosen for the following reasons: polystyrene is currently the most popular choice (Eftimie 2017), and sheep wool is an ecological, renewable material with comparable thermal insulation capabilities, which is to be found in abundance in Bukovina. Even though in terms of thermal performance polystyrene showed on average an 8% lower heating demand compared to sheep wool insulation, the Life Cycle Analysis places sheep wool insulation at a competitive level.

In terms of annual heating demand, after improving the thermal resistance of the building envelope with either sheep wool or polystyrene thermal insulation, all houses went from being certified with class C performance level to being certified with class A performance level, according to the current Romanian building regulations, and show no sign of overheating.

The study suggests that old houses in the region of Bukovina in their current state do present disadvantages in terms of energy efficiency, but these can be improved through renovation. 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.

6.2. FUTURE RESEARCH

This study is based on dynamic thermal simulations made with help of the EDSL TAS software. Actual measurements of the indoor environment, with properly documented occupancy, occupant behaviors and air exchange rates of the houses would give a more accurate picture over what changes need to be made in order to achieve thermal comfort under current requirements.

It would also be interesting to investigate to which extent it is feasible to try and bring these houses to a passive house energy efficiency level, if overheating would be a problem, and in that case, finding a cost efficient solution to reduce or eliminate the cooling demand.

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8. Appendix

8.1. BUILDING CONSTRUCTIONS OF THE ASSESSED HOUSES

8.1.1. House 1, Cases W and W+

Table 16 Building materials of House 1_Cases W and W+

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	250	0,115	545	2.720
Grey clay	5	0,33	1.025	1.063
Inside wall				
Lime plaster	2	0,70	1.600	837
Brick	190	0,60	1.750	920
Lime plaster	2	0,70	1.600	837
Ground floor slab (to basement)				
Fir wood planks	50	0,115	545	2.720
Fir wood beams	300	0,115	545	2.720
Ceiling to attic				
Clay	10	0,33	1025	2.720
Fir wood planks	50	0,115	545	2.720
Fir wood beams	250	0,115	545	2.720
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Wool insulation	80	0,039	19	1.700
Chip board	22	0,110	700	1.570
Wool insulation	80	0,039	19	1.700
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Window house				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Single glazing window	6	5,68	0,57	0,51
Window annex				
Double glazing window	24	1,18	0,29	0,16

8.1.2. House 2, Cases W and W+

Table 17 Building materials of House 2_Cases W and W+

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Lime plaster	2	0,70	1.600	837
Clay	20	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,60	1.750	920
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Floor to the ground				
Beaten earth	150	1,298	1.900	2.720
Clay	50	0,33	1.025	2.720
Straw	50	0,05	25	610
Sand	50	0,329	1.515	796
Gravel	200	0,84	1.760	1.063
Ceiling to attic				
Clay	10	0,33	1.025	2.720
Fir wood planks	50	0,115	545	2.720
Fir wood beams	250	0,115	545	2.720
Fir wood slats	24	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Roof cladding	6	0,115	545	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Roof laths	30	0,115	545	2.720
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0.115	545	2.720
Window				
Window type	**Width [mm]**	**U-Value [Wm^{-2}K^{-1}]**	**G-Value [Wm^{-2}K^{-1}]**	**Solar transmittance**
Single glazing window	6	5,68	0,57	0,51

8.1.3. House 3, Cases W and W+

Table 18 Building materials of House 3_Cases W and W+

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
House outside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Grey clay	2	0,33	1.025	1.063
Lime plaster	5	0,70	1.600	837
Workshop outside wall				
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
House floor to the ground				
Fir wood slats	24	0,115	545	2.720
Wool felt underlay	100	0,04	160	1.360
Fir wood planks	80	0,115	545	2.720
Sand	50	0,329	1.515	796
Gravel	100	0,84	1.760	1.063
Workshop floor to ground				
Beaten earth	150	1,298	1.900	2.720
Clay	100	0,33	1.025	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Sand	50	0,329	1.515	796
Gravel	200	0,84	1.760	1.063
Ceiling to attic				
Clay	10	0,33	1.025	2.720
Fir wood planks	50	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Wool insulation	80	0,039	19	1.700
Chip board	22	0,110	700	1.570
Wool insulation	80	0,039	19	1.700
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Window house				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Single glazing window	6	5,68	0,57	0,51
Window annex				
Double glazing window	24	1,18	0,29	0,16

8.1.4. House 4, Cases W and W+

Table 19 Building materials of House 4_Cases W and W+

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Lime plaster	2	0,70	1600	837
Clay	20	0,33	1025	1063

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Fir wood beams	200	0,115	545	2720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	180	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Floor to the ground				
Beaten earth	150	1,298	1.900	2.720
Clay	50	0,33	1.025	2.720
Straw	50	0,05	25	610
Sand	50	0,329	1.515	796
Gravel	200	0,84	1.760	1.063
Ceiling to attic				
Clay	10	0,33	1.025	2.720
Fir wood planks	50	0,115	545	2.720
Fir wood beams	300	0,115	545	2.720
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Wool insulation	80	0,039	19	1.700
Chip board	22	0,110	700	1.570
Wool insulation	80	0,039	19	1.700
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Window house				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Single glazing window	6	5,68	0,57	0,51
Window annex				
Double glazing window	24	1,18	0,29	0,16

8.1.5. House 1, Case INS_SW

Table 20 Building materials of House 1_Case INS_SW

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Gypsum plasterboard	15	0,17	800	891
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	80	0,0385	18	1.760
Wind seal	1	0,5	30	1.260
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	250	0,115	545	2.720
Grey clay	5	0,33	1.025	1.063
Inside wall				
Lime plaster	2	0,70	1.600	837
Brick	190	0,60	1.750	920
Lime plaster	2	0,70	1.600	837
Ground floor slab (to basement)				
Fir wood flooring	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Sheep wool	300	0,0385	18	1.760
Vapor barrier	0,2	0,5	30	1.260
Gypsum plasterboard	15	0,17	800	891
Floor to the ground				
Fir wood flooring	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Sheep wool	300	0,0385	18	1.760
Support mesh / Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Sheep wool	160	0,0385	18	1.760
Support mesh / Vapor barrier	0.2	0,5	30	1.260
Clay	10	0,33	1.025	2.720
Fir wood planks	24	0,115	545	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Roof				
Wood shingles	6	0,115	545	2.720
Roof battens	30	0,115	545	2.720
Vapor diffuser	0.2	0,5	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Sheep wool	80	0,039	18	1.760
Chip board	22	0,110	700	1.570
Sheep wool	80	0,0385	18	1.760
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.6. House 2, Case INS_SW

Table 21 Building materials of House 2_Case INS_SW

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Gypsum plasterboard	15	0,17	800	891
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	80	0,0385	18	1.760
Wind seal	1	0,5	30	1.260
Lime plaster	2	0,70	1.600	837
Clay	20	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity $[W.m^{-1}.K^{-1}]$**	**Density $[kg.m^{-3}]$**	**Heat capacity $[J.kg^{-1}.K^{-1}]$**
Fir wood beams	150	0,60	1.750	920
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Floor to the ground				
Fir wood flooring	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Sheep wool	300	0,0385	18	1.760
Support mesh / Vapor barrier	2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	240	0,0385	18	1.760
Support mesh / Vapor barrier	2	0,5	30	1.260
Fir wood slats	24	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Vapor diffuser				
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Window				
Window type	**Width [mm]**	**U-Value $[W.m^{-2}.K^{-1}]$**	**G-Value $[W.m^{-2}.K^{-1}]$**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.7. House 3, Case INS_SW

Table 22 Building materials of House 3_Case INS_SW

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
House outside wall				
Gypsum plasterboard	15	0,17	800	891
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	80	0,0385	18	1.760
Wind seal	1	0,5	30	1.260
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Grey clay	2	0,33	1.025	1.063
Lime plaster	5	0,70	1.600	837
Workshop outside wall				
Gypsum plasterboard	15	0,17	800	891
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	80	0,0385	18	1.760
Wind seal	1	0,5	30	1.260
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
House floor to the ground				
Fir wood flooring	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Sheep wool	300	0,0385	18	1.760
Support mesh / Vapor barrier	2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Workshop floor to ground				
Fir wood flooring	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Sheep wool	240	0,0385	18	1.760

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Support mesh / Vapor barrier	2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Clay	10	0,33	1.025	2.720
Fir wood planks	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	160	0,0385	18	1.760
Support mesh / Vapor barrier	2	0,5	30	1.260
Fir wood planks	24	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Wood shingles	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Vapor barrier	0.2	0,5	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Sheep wool	80	0,0385	18	1.760
Chip board	22	0,110	700	1.570
Wool insulation	80	0,039	19	1.760
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.8. House 4, Case INS_SW

Table 23 Building materials of House 4_Case INS_SW

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
		Outside wall		
Gypsum plasterboard	15	0,17	800	891
Vapor barrier	0,2	0,5	30	1.260
Sheep wool	80	0,0385	18	1.760
Wind seal	1	0,5	30	1.260
Lime plaster	2	0,70	1.600	837
Clay	20	0,33	1.025	1.063
Fir wood beams	200	0,115	545	2.720
		Inside wall		
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	180	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
		Floor to the ground		
Fir wood flooring	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Sheep wool	300	0,0385	18	1.760
Support mesh / Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
		Ceiling to attic		
Fir wood planks	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood beams	-	0,115	545	2.720
Sheep wool	200	0,0385	18	1.760
Support mesh / Vapor barrier	2	0,5	30	1.260
Fir wood planks	24	0,115	545	2.720
		Roof		
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Vapor barrier	1	0,17	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Sheep wool	80	0,0385	18	1.760
Chip board	22	0,110	700	1.570
Sheep wool	80	0,0385	18	1.760
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.9. House 1, Case INS_P

Table 24 Building materials of House 1_Case INS_P

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Gypsum plasterboard	12,5	0,17	800	891
Adhesive	3	0,33	1.025	1.063
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Wind foil	0,2	0,120	30	1.260
Wood slats/ ventilation layer	20	0,115	545	2.720
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	250	0,115	545	2.720
Grey clay	5	0,33	1.025	1.063
Inside wall				
Lime plaster	2	0,70	1.600	837
Brick	190	0,60	1.750	920
Lime plaster	2	0,70	1.600	837

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Ground floor slab (to basement)				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Fir wood joists	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gypsum plasterboard	15	0,17	800	891
Floor to the ground				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Bituminous membrane	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood beams	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Supporting mesh / Vapor barrier	0,2	0,5	30	1.260
Clay	10	0,33	1.025	2.720
Fir wood planks	24	0,115	545	2720
Roof				
Wood shingles	6	0,115	545	2.720
Roof battens	30	0,115	545	2.720
Vapor diffuser	0,2	0,5	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	12,5	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Chip board	22	0,110	700	1.570

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1025	1.063
Gray clay	3	0,330	1025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.10. House 2, Case INS_P

Table 25 Building materials of House 2_Case INS_P

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Gypsum plasterboard	12,5	0,17	800	891
Adhesive	3	0,33	1.025	1.063
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Wind foil	0,2	0,120	30	1.260
Wood slats/ ventilation layer	20	0,115	545	2.720
Lime plaster	2	0,70	1.600	837
Clay	20	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,60	1.750	920
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Floor to the ground				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Bituminous membrane	0,2	0,5	30	1.260

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Fir wood joists	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	2	0,5	30	1.260
Fir wood slats	24	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Vapor diffuser				
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Window				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.11. House 3, Case INS_P

Table 26 Building materials of House 3_Case INS_P

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
House outside wall				
Gypsum plasterboard	12,5	0,17	800	891
Adhesive	3	0,33	1.025	1.063
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Wind foil	0,2	0,120	30	1.260

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Wood slats/ ventilation layer	20	0,115	545	2.720
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Fir wood slaps	10	0,115	545	2.720
Grey clay	2	0,33	1.025	1.063
Lime plaster	5	0,70	1.600	837
Workshop outside wall				
Gypsum plasterboard	12,5	0,17	800	891
Adhesive	3	0,33	1.025	1.063
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Wind foil	0,2	0,120	30	1.260
Wood slats/ ventilation layer	20	0,115	545	2.720
Fir wood beams	150	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	150	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
House floor to the ground				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Bituminous membrane	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Workshop floor to ground				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Bituminous membrane	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Extruded Polystyrene (XPS)	240	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Fir wood beams	-	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Extruded Polystyrene (XPS)	160	0,035	22	1.500
Support mesh / Vapor barrier	2	0,5	30	1.260
Fir wood planks	24	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Roof				
Wood shingles	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	12,5	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Chip board	22	0,110	700	1.570
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.1.12. House 4, Case INS_P

Table 27 Building materials of House 4_Case INS_P

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Outside wall				
Gypsum plasterboard	12,5	0,17	800	891
Adhesive	3	0,33	1.025	1.063
Expanded Polystyrene (EPS)	80	0,035	22	1.500
Wind foil	0,2	0,120	30	1.260
Wood slats/ ventilation layer	20	0,115	545	2.720
Lime plaster	2	0,70	1.600	837
Clay	20	0,33	1.025	1.063
Fir wood beams	200	0,115	545	2.720
Inside wall				
Lime plaster	2	0,70	1.600	837
Clay	10	0,33	1.025	1.063
Fir wood beams	180	0,115	545	2.720
Clay	10	0,33	1.025	1.063
Lime plaster	2	0,70	1.600	837
Floor to the ground				
Fir wood flooring	24	0,115	545	2.720
OSB	20	0,13	650	
Bituminous membrane	0,2	0,5	30	1.260
Fir wood joists	-	0,115	545	2.720
Extruded Polystyrene (XPS)	300	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Gravel	240	0,84	1.760	1.063
Ceiling to attic				
Fir wood planks	50	0,115	545	2.720
Vapor barrier	0,2	0,5	30	1.260
Fir wood beams	-	0,115	545	2.720
Extruded Polystyrene (XPS)	200	0,035	22	1.500
Vapor barrier	0,2	0,5	30	1.260
Fir wood planks	50	0,115	545	2.720
Roof				
Roof cladding	6	0,115	545	2.720
Roof laths	30	0,115	545	2.720

Layers (inside to outside / top to bottom)	**Width [mm]**	**Thermal conductivity [W.m^{-1}.K^{-1}]**	**Density [kg.m^{-3}]**	**Heat capacity [J.kg^{-1}.K^{-1}]**
Vapor barrier	1	0,17	30	1.260
Fir roof decking	24	0,115	545	2.720
Fir wood beams	140	0,115	545	2.720
Outside wall annex				
Gypsum plasterboard	15	0,22	800	1.088
Vapor barrier	1	0,17	30	1.260
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Chip board	22	0,110	700	1.570
Expanded Polystyrene (EPS)	80	0,035	35	1.500
Fir wood planks	24	0,115	545	2.720
Yellow clay	5	0,288	1.025	1.063
Gray clay	3	0,330	1.025	1.063
Windows				
Window type	**Width [mm]**	**U-Value [W.m^{-2}.K^{-1}]**	**G-Value [W.m^{-2}.K^{-1}]**	**Solar transmittance**
Double glazing window	24	1,18	0,29	0,16

8.2. ZONING IN EDLS TAS

8.2.1 Zoning of House 1

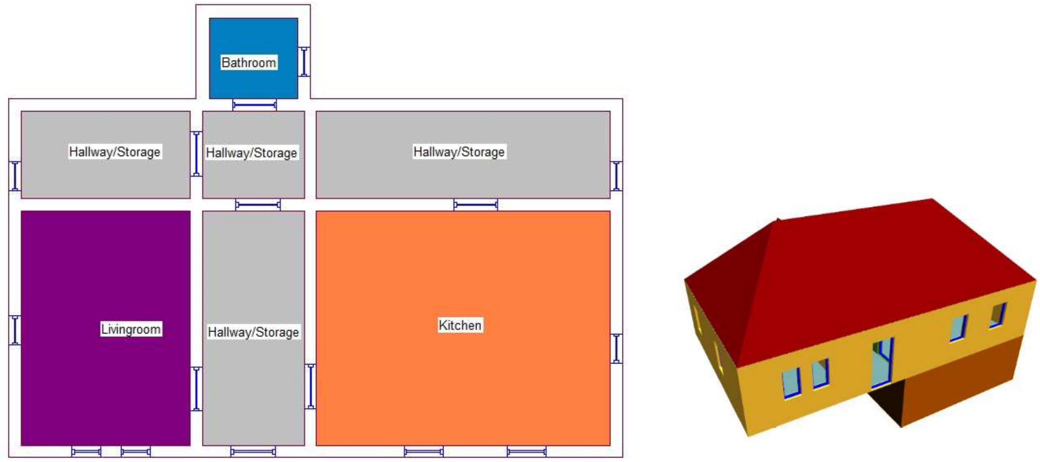

Figure 64 Ground floor plan of House 1 colored by zones

Table 28 Zones in House 1 associated with floor areas and volumes

Name of zone	Color	Area [m^2]	Volume [m^3]
Livingroom	🟪	16,6	39,5
Kitchen	🟧	28,8	68,7
Hallway/Storage	⬜	30,8	73,5
Bathroom	🟦	4,0	8,0

8.2.2 Zoning of House 2

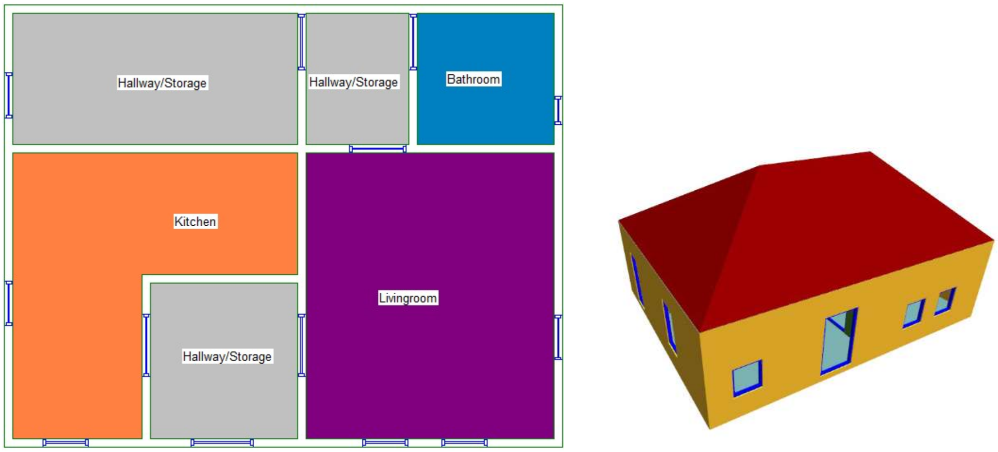

Figure 65 Ground floor plan of House 2 colored by zones

Table 29 Zones in House 2 associated with floor areas and volumes

Name of zone	**Color**	**Area [m^2]**	**Volume [m^3]**
Livingroom	🟪	22,5	56,2
Kitchen	🟧	17,7	44,2
Hallway/Storage	⬜	23,4	58,6
Bathroom	🟦	5,7	14,2

8.2.3 Zoning of House 3

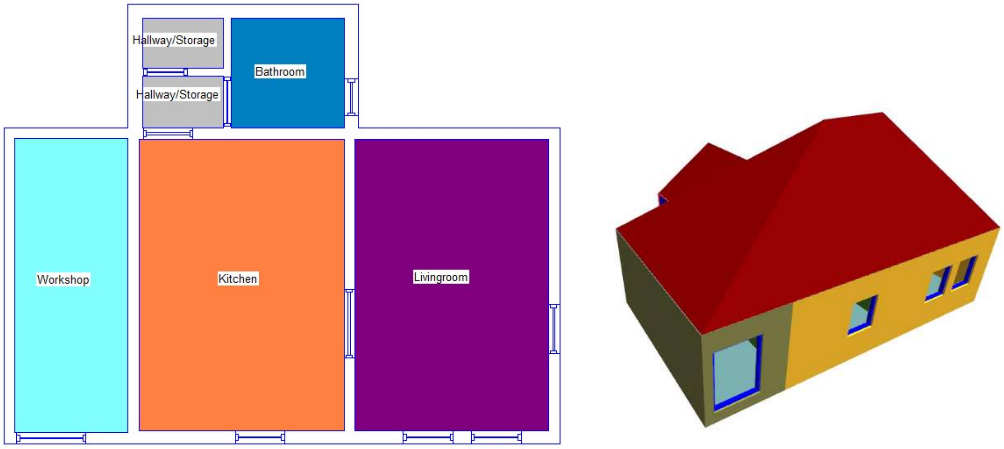

Figure 66 Ground floor plan of House 3 colored by zones

Table 30 Zones in House 3 associated with floor areas and volumes

Name of zone	Color	Area [m^2]	Volume [m^3]
Livingroom	🟪	14,8	27,9
Kitchen	🟧	15,6	29,6
Workshop	🟦	8,7	16,5
Hallway/Storage	⬜	2,1	4,0
Bathroom	🟦	4,0	8,0

8.2.4 Zoning of House 4

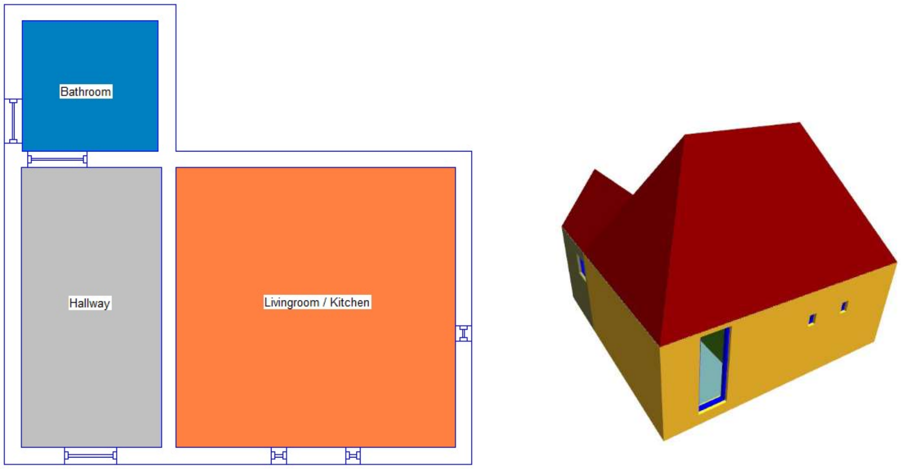

Figure 67 Ground floor plan of House 4 colored by zones

Table 31 Zones in House 4 associated with floor areas and volumes

Name of zone	**Color**	**Area [m^2]**	**Volume [m^3]**
Livingroom/Kitchen	🟧	14,4	28,9
Hallway	⬜	7,2	14,4
Bathroom	🟦	4,0	8,0

8.3. WEATHER DATA

Table 32 Weather data of Suceava, Romania (Climate Consultant)

Month	**Average temperature**	**Average global radiation**	**Average diffuse radiation**	**Average humidity**
	[°C]	**[W.m^{-2}]**	**[W.m^{-2}]**	**[%]**
January	-4	152	92	88
February	-2	223	121	82
March	1	271	156	83
April	8	372	178	74
May	14	406	204	73
June	16	464	210	76
July	18	456	193	75
August	17	458	176	76
September	13	353	163	78
October	8	279	129	80
November	2	156	96	86
December	-1	103	68	88