Case study regarding the energy efficiency of a modular house having ecological envelope

Studiu de caz privind eficiența energetică a unei case modulare cu anvelopa ecologică

Georgiana Corsiuc[1], Carmen Mârza[2].

[1]Universitatea Tehnică din Cluj-Napoca, Facultatea de Instalații
B-dul 21 Decembrie 1989, nr. 128-130, Cluj Napoca, România
E-mail: georgiana@mail.utcluj.ro

[2] Universitatea Tehnică din Cluj-Napoca, Facultatea de Instalații
B-dul 21 Decembrie 1989, nr. 128-130, Cluj Napoca, România
E-mail: carmen.marza@insta.utcluj.ro

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Abstract. *In this paper, the authors propose a case study on the energy efficiency of a house built in accordance with sustainable development directions. Thus, the envelope is made of ecological materials, namely the resistance structure and finishes are made of wood, and the thermal insulation of sheep's wool. It is a modular, prefabricated house, designed so that energy consumption is reduced both in the construction and exploitation phase. Having a built area of 31.5 m^2, it can be used as a residential house or a holiday home. For this, the thermotechnical properties of the envelope elements were studied.*

Key words: ecological construction, energy efficiency, envelope structure, thermal resistance, heat transfer coefficient, thermal stability, water vapor permeability.

1. Introduction

Two of the fundamental challenges of our times, namely the energy and the environment, significantly concern the field of civil engineering.

In the last few years, one has faced the pandemic problem caused by Sars Cov 19 which has changed people's mentality and generated their desire to "migrate" from crowded urban areas to more isolated areas, which was possible due to the work and education in the online system, through various platforms. On the other hand, the energy problem that has been in the attention of society since the last decades of the 20th century, has become acute nowadays due to the political situation created by the conflict generated by the Russian Federation, which represented an important supplier of fossil fuels for many states in the Union European and beyond. In this complicated context, a significant number of people have chosen to ensure alternative residences. A practical solution is represented by modular houses - as a quick construction method, which must be as ecological as possible, energy efficient and having independence from the centralized energy system if the energy is provided from renewable sources.

As it is known, an ecological house can be defined synthetically, as a house built and exploited with a lot of responsibility towards the environment, during its entire life cycle, starting with the design phase, then construction, maintenance, renovation, including also the demolition phase [1].

As a result of global statistics, yields that about 40% of the total energy consumption is due to constructions, including the construction itself and its exploatation, so that the microclimate conditions required by the occupants are ensured.

Regarding the heat losses through the envelope, results that these have the following structure: about 35% through the walls, 30% through the roofs, 20% through the glazed surfaces, respectively 15% through the floors. Although this information are relative, it is useful to have an overview of the selection of materials and solutions related to the elements of the envelope, having the main goal to improve the energy performance of buildings [2].

Considering the previous information, the authors proposed a solution for the construction of a modular house, made of ecological materials and carried out a study regarding the thermotechnical properties of the envelope elements, respectively for the external walls and for the covering. Moreover, the use of wood in the construction of residential houses is recommended on the one hand due to the creation of a healthy microclimate in the homes, and on the other hand due to the low thermal conductivity coefficient, which is approximately 7-10 times higher than to concrete, respectively 3-4 times compared to brick [3].

2. Presentation of the proposed house and analysis of thermotechnical properties

2.1. The plan of the house and the main hygrothermal properties

The modular house proposed to the beneficiaries considered their requests regarding the dimensions, partitioning, construction materials and obviously the costs. The envelope plays an important role in achieving and maintaining the comfort conditions for a construction in the general way and implicitly in the case of ecological houses. In short, it separates the heated volumes of the construction from the external environment and from other elements characterized by different temperatures, which are in contact with it [4]. Fig. 1 presents the floor plan of the house, having a constructed area of 31.5 m^2.

In fact, the house was designed at the request of some beneficiaries from a rural, semi-montane area in Austria, having a placement similar to climate zone III in our country, i.e., the exterior temperature of -18 ^oC. For these conditions, the verification of the requirements related to the hygrotemic behavior of the envelope elements was carried out using the Ubakus U-value calculator [5].

Following, are presented the measurements that are automatically calculated, obviously according to the proposed structure for the elements.

Thus, related to thermal protection, the following physical quantities are obtained:

- specific thermal resistance R [m^2K/W] → defines the property of the materials through which the heat is transferred to oppose the propagation of heat losses; in the case of a construction element consisting of several homogeneous layers, it represents the sum of the convective resistances of the fluid media (air) in the vicinity of the element and the actual conductive resistance of the element [4], [6];
- heat transfer coefficient (or transmittance) [W/m^2K], represents the reverse of the thermal resistance; it reflects the heat transfer capacity, so the lower the U value is, the lower the transmission losses are [4], [6];
- temperature variation within the structure of the envelope elements and the surface temperatures, which gives an image of heat losses and reflects the possibility of condensation risk of [6], [7].

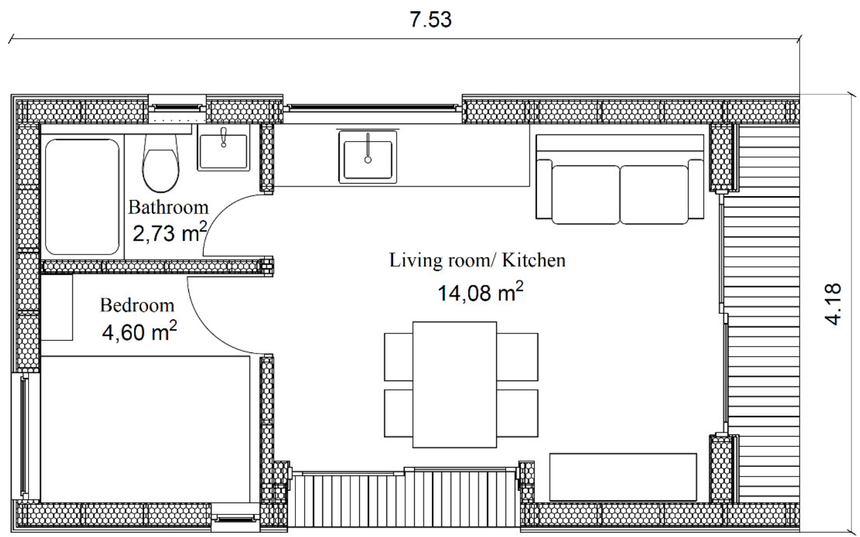

Fig. 1. The floor plan of the modular ecological house

An important interest and facility that this program provides are related to the thermal stability of the closing elements and not of the rooms as whole. The thermal stability of buildings represents their ability to maintain the amplitudes of the variations of the indoor air temperature and the temperatures of the interior surfaces of the elements within the admissible limits, required by the compliance of the indoor thermal comfort conditions [4], [6], [7].

Thus, depending on the layers that build up the closing element, it results:

- The phase shift coefficient, represents the time in hours after which the temperature peak of the afternoon reaches the component interior and has usually values between 6 and 14 hours, depending on the thermotechnical properties of the materials [4], [6], [7];
- The amplitude attenuation coefficient of the outdoor air oscillation, which is defined as the ratio between the outdoor air temperature oscillation amplitude and the temperature oscillation amplitude it determines on the inner surface of

the building element; it is dimensionless, and it is recommended to be contained within the range 16 … 25 [4], [6], [7].

These coefficients are also normed in Romanian standards.

The Ubakus program implicitly calculates other quantities, such as the temperature amplitude - as the reverse of the previous coefficient, the heat storage capacity, the thermal capacity of the inner layers, etc. [5].

From the point of view of the vapor permeability of the envelope elements, the Ubakus calculation program provides graphs that show how the relative humidity varies in the wall structure [5]. It also implicitly calculates a quantity **Sd**, which represents the vapor diffusion resistance of the construction elements, which the Romanian standards did not provide in this form. This represents the equivalent thickness of the air layer to the diffusion of water vapor, and is calculated with the formula:

$$Sd = \mu \times d \text{ [m]} \qquad (1),$$

where, μ= vapor diffusion resistance coefficient, depending on the material,

d= the thickness of the material layer subjected to vapor transition [m].

The lower the value, the less resistance the building element opposes and allows vapor to diffuse more easily.

2.2. Exterior walls

In the following, the thermotechnical properties that the Ubakus application [5] generates, depending on the structure proposed by the authors, are presented, namely:

- Figure 2 shows the constructive structure of the external walls;
- a section through the wall is shown in Figure 3;
- Figure 4 shows the oscillation of the surface temperature during one day and the phase shift of the heat wave propagation;
- Figure 5 shows the variation of relative humidity in the wall structure.

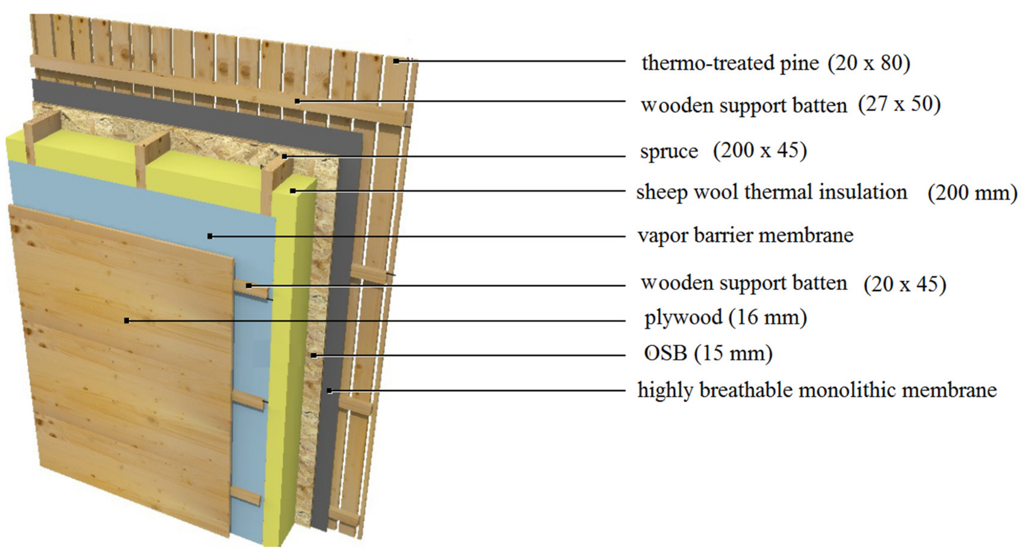

Fig.2. The constructive structure of the external walls

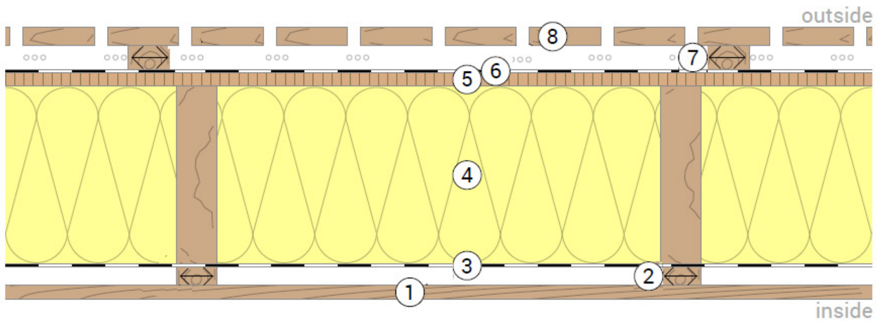

Fig.3. Section through the exterior wall

1. Plywood; 2. Wooden support batten; 3. Vapor barrier membrane; 4. Sheep wool thermal insulation; 5. OSB board; 6. Highly breathable monolithic membrane resistant to uv rays; 7. Wooden support batten; 8. Thermo-treated pine facade.

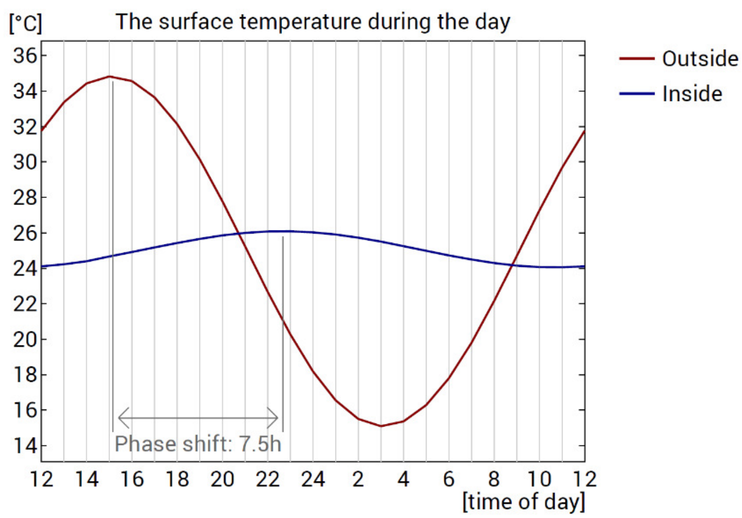

Fig.4. The surface temperature during the day

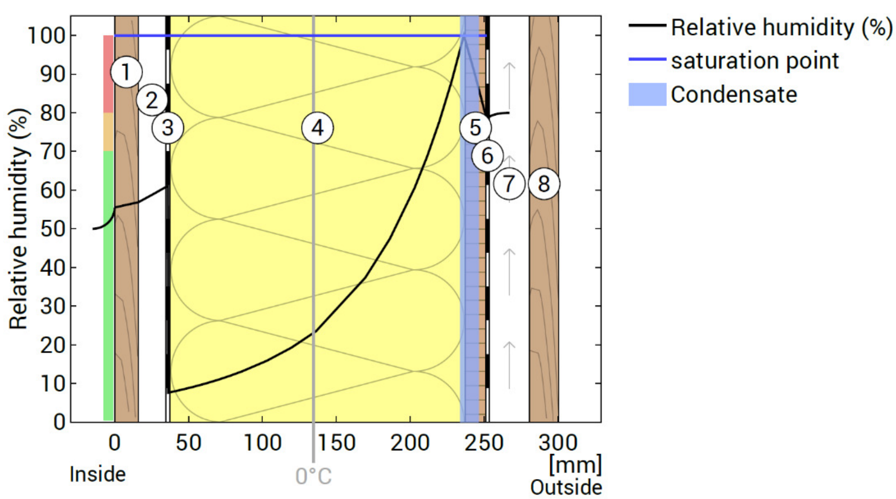

Fig.5. The relative humidity inside the component

Table 1 shows the physical dimensions that characterize the thermal protection of the external wall components. In addition, the program directly calculates the heat transfer coefficient of the external wall, i.e. U = 0.2 W/m2K. This value complies with the recommendations of the ISO standard [8], being close to the requirements imposed on an energy-efficient house.

Table 1

The hygrothermal properties of the external wall components

Material	Thickness [cm]	Thermal conductivity [W/mK]	Thermal resistances [m2K/W]	Sd-value [m]
Thermal contact resistance (Rsi)			0.130	
Plywood	1.60	0.160	0.100	0.80
Stationary air	2.00	0.114	0.175	0.01
Wooden support batten (8.3%)	2.00	0.130	0.154	
Vapor barrier membrane	0.02	0.400	0.001	40.00
Sheep wool thermal insulation	20.00	0.039	5.195	0.20
Wooden support batten (8.3%)	20.00	0.130	1.538	4.00
OSB board	1.50	0.130	0.115	3.00
Highly breathable monolithic membrane	0.1	0.200	0.005	0.10
Thermal contact resistance (Rse)			0.040	
Whole component	29.17		5.03	

2.3. The roof

As in the case of the walls, the thermotechnical characteristics of the covering that the Ubakus application [5] generates, depending on the structure proposed by the authors, are presented, namely:

- Figure 6 shows the construction elements of the covering;
- Figure 7 shows a section through the covering;
- Figure 8 shows the oscillation of the surface temperature during one day and the phase shift of the heat wave propagation;
- Figure 9 shows the variation of relative humidity in the structure of the covering.

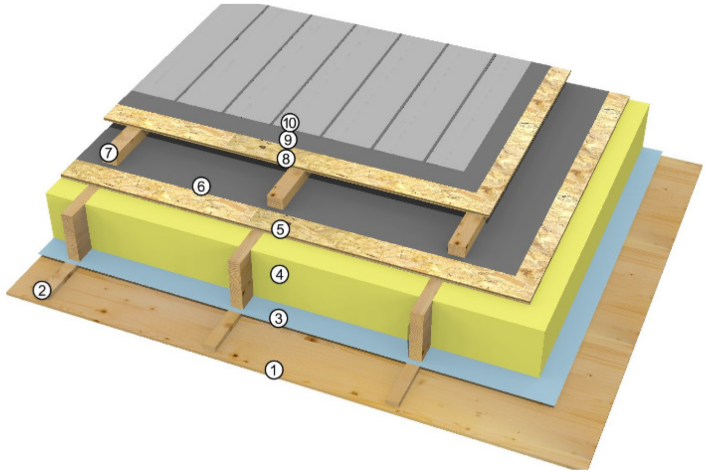

Fig.6. The constructive structure of the covering

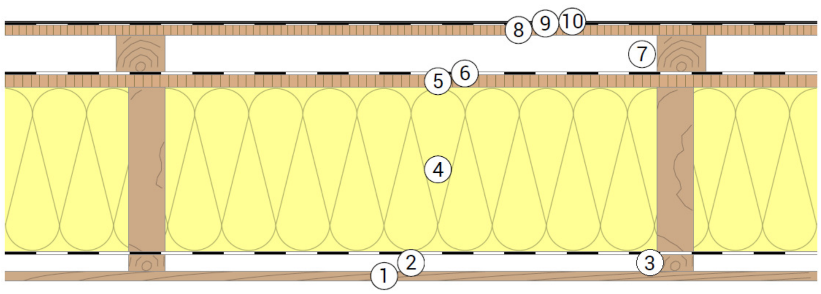

Fig.7. Section through the roof

1.Plywood; 2. Wooden support batten; 3. Vapor barrier membrane; 4. Sheep wool thermal insulation; 5. OSB board; 6. Highly breathable monolithic membrane resistant to uv rays; 7. Wooden support batten; 8. OSB board; 9. Highly breathable monolithic membrane resistant to uv rays; 10.Metal sheet.

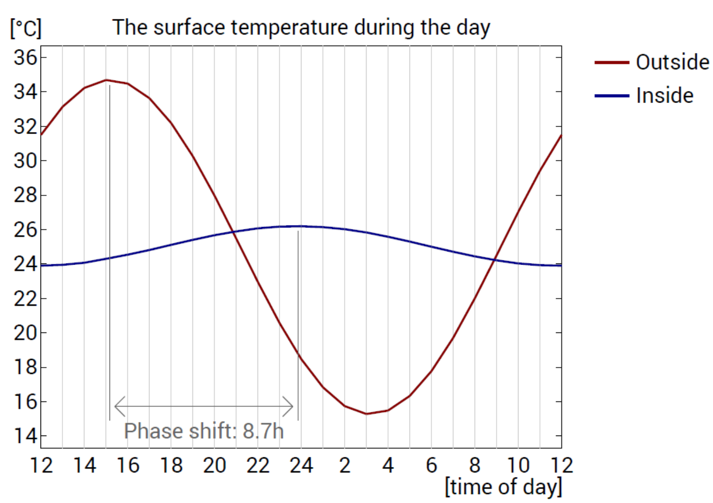

Fig.8. The surface temperature during the day

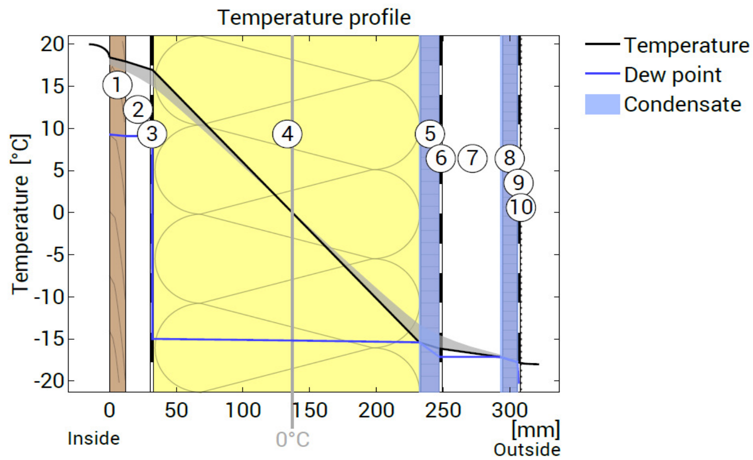

Fig.9. The relative humidity inside the component

Table 2 shows the physical quantities that characterize the thermal protection of the component elements of the covering. Once more, the program directly calculates the heat transfer coefficient, namely U = 0.19 W/m2K. With these values, the chosen solution falls within the norms agreed in Austria [8].

Table 2

The hygrothermal properties of the component elements in the envelope

Material	Thickness [cm]	Thermal conductivity [W/mK]	Thermal resistances [m2K/W]	Sd-value [m]
Thermal contact resistance (Rsi)			0.100	
Plywood	1.20	0.160	0.075	0.60
Stationary air	2.00	0.125	0.160	0.01
Wooden support batten (7%)	2.00	0.130	0.154	0.80
Vapor barrier membrane	0.02	0.400	0.001	40.00
Sheep wool thermal insulation	20.00	0.039	5.195	0.20
Wooden support batten (7%)	20.00	0.130	1.538	4.00
OSB board	1.50	0.130	0.115	3.00
Highly breathable monolithic membrane	0.07	0.300	0.002	0.02
Stationary air	4.5	0.281	0.160	0.01
Wooden support batten (9.1%)	4.5	0.130	0.346	1.8
OSB board	1.20	0.130	0.0.92	2.40
Highly breathable monolithic membrane	0.07	0.300	0.002	0.02
Metal sheet	0.10	10.000	0.000	1500
Thermal contact resistance (Rse)			0.040	
Whole component	30.66		5.32	

3. Conclusions

In this paper, the authors proposed and presented, structures for the envelope elements - external walls and covering, to meet as many requirements and demands as possible, among which we briefly mention the most important ones:

• to have good hygrothermal properties, i.e. to ensure good thermal protection, thermal stability of the closing elements, appropriate vapor permeability behavior, without

allowing the accumulation of water in the structure of the envelope elements;
• to be constructed quickly, to be transportable by road – the house having the destination in Austria, to have an acceptable weight, to be easy to assemble and handle; obviously, wooden constructions are very suitable for these requirements;
• to use environmentally friendly materials that can be recycled or reused.

In this sense, one mention the use of wood as the main construction material and sheep's wool, for thermal insulation respects the requirements of an ecological house. Wool must be pre-treated for pest protection with urea derivatives, and for fire and mold protection with boron salts. However, its special thermotechnical properties especially recommend it, even if other solutions could generate lower costs.

Finally, in Figure 10 are given photos of the studied house.

Fig.10. Photos of the studied house

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