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# USING PASSIVE DESIGN STRATEGIES TO IMPROVE THERMAL PERFORMANCE OF SINGLE FAMILY HOUSES. A COMPARATIVE STUDY

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**Abstract**

In recent years there is a general consensus on the issues regarding climate change and the exceeding $CO_2$ emissions, in which the housing sector plays a crucial role, prompting the need to rethink the way buildings are designed. Implementing ecological houses is most often achieved at very high costs and without a real concern for archetypical typologies, thus responding inadequately to main sustainability criteria regarding economy and society. Current research in the field of construction is targeting these aspects, with the purpose of achieving near zero energy houses with affordable costs and integrating cultural values. In this context, the main objective of the research has been the development of a highly energy efficient single-family dwelling, in accordance with the Romanian housing tradition, with minimum impact on the environment and also economically accessible to different social categories. In order to accomplish this goal several strategies have been implemented, such as: use of natural local materials (wool, wood and clay), revival of traditional construction techniques, use of thermal mass for construction elements and integration of solar passive design. Multi-criteria energy simulations have been performed for the optimisation of the proposed design.

*Keywords:* near zero energy buildings, renewable resources, sustainability assessment methods, traditional materials

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## 1. Introduction

*Article 3 of Energy Performance of Buildings Directive (EBPD)* (EU Directive 31, 2010) stipulates that by 2020 all new constructions should be graded Near Zero Energy Buildings (NZEB). The 2015 UN Climate Change Conference, held in Paris, emphasizes the role of increasing energy efficiency as means for reducing greenhouse gas emissions (Obergassel et al., 2015). Moreover, latest research regarding climate change demands more active energy optimisation measures in the construction sector, including small dwellings (Kadhim-Abid et al., 2019). In this context, the concern for energy efficiency of residential buildings influences optimization of both design and constructive solutions in accordance with NZEB framework (Chastas et al., 2016). Regarding the situation in the last decades in Romania, it is noted a special interest for construction of single-family houses, aspect explained as a reaction to the generalization of collective housing imposed by the former communist regime (Vais, 2009).

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In terms of energy efficiency, the single-family dwelling has the following features:

- due to unfavourable ratio between external perimeter and heated volume, a single-family dwelling has a lower energy performance, in the range of 30% - 40% of an apartment with the same geometric characteristics and degree of insulation, that is part of a collective housing unit (Santamouris, 2006);
- in the condition in which the maximum thermal insulation level, limited by the optimal cost, has been reached, the increase of the energy performance can be achieved exclusively through passive design strategies (DeKay and Brown, 2014);
- specific passive design strategies, including a wide variety of systems, solutions and materials, are much easier to integrate into single-family home projects, contributing significantly to their architectural expressiveness (Thomas, 2006).

In this context, a research group from the "G. M. Cantacuzino" Faculty of Architecture of Iași conducted the UFSCDI MODELLUS project. This was a technology transfer project which aimed at developing a single-family house model, more efficient, in terms of energy performance and environmental impact, than the Sibelius wooden house in Suceava.

The present proposal falls within the specific category related to implementation of EU stipulations interlinking university's expertise in the field with the economic agent's needs. The concept of the new house model and selection of energy efficiency strategies were based on critical analysis of the already existing building, taking into account the architectural, thermal performance and indoor air quality standpoints. The paper presents the design stages, new model optimization and performance levels obtained by numerical simulations in comparison with those of Sibelius wooden solar house.

## 2. Technology provided by the economic agent: the Sibelius wooden solar house

### *2.1. Overview, passive design strategies*

The economic agent involved in the project is both the owner and promoter of high energy performance building technologies with minimal environmental impact, already applied to a demonstrative building, also known as "Sibelius Solar house with wooden structure".Passive systems for the recovery of energy from renewable sources (solar radiation), ventilation optimization, solar energy collectors, storage systems, etc., make an important contribution to reducing consumption to ensure a healthy and comfortable environment. These energy-related aspects were considered in implementation of an experimental single-family dwelling, "Sibelius wooden solar house", in the city of Suceava, intended for replication and commercialization (Fig. 1).

The solar house has been built in 2014. The indoor usable area is 240 $m^2$ and the house's total investment value has reached 350000 Euros. From an architectural standpoint, the element of interest is a transparent, centrally-located greenhouse, around which the other functions are organized ("the heart of the house"). This green space acts as a passive system for capturing solar radiation through direct input. Similarly, the highly glazed vertical surfaces, rationally oriented South and South-West, also work as passive collectors as well as providing an optimal level of daytime illumination thus helping to reduce the number of hours in which artificial lighting.

The building has a high thermal protection level, the enclosure elements being made of wood panels with cellulosic thermal insulation and high-performance glazing, characterized by the following thermal transmittances: 0.15 $W/m^2K$ - walls, 0.10 $W/m^2K$ - roof and 0.7 $W/m^2K$ - glazed surfaces.

**Fig. 1.** Sibelius Solar house, front and back overview

### *2.2. Energy and environmental performance*

The most important indicators for thermal-energy characterization of a building are:

- *global coefficient of thermal insulation (G)* expressed in W/m$^3$K, which takes into account heat losses through transmission and ventilation and allows characterization of building in terms of volumetric compliance (building envelope area related to the heated volume), indicating the comfort degree and allowing, in the design stage, the selection of solutions for building's skin optimization (Secu and Romila, 2014);
- specific annual energy consumption for heating ($q_i$),expressed in kWh/m$^2$a, which represents the energy of a heated / usable surface unit, necessary to achieve comfort conditions during the winter season; is determined by taking into account the thermal mass of the building, the efficiency of the heating installation and the solar inputs depending on the orientation (Hopfe and McLeod, 2015);
- specific annual energy consumption for cooling ($q_r$),expressed in kWh/m$^2$a, which represents the energy, necessary to achieve comfort conditions during the summer season for a usable surface unit; it is determined by taking into account building orientation, the nature of the glazed surfaces, the presence of vegetation and the protection systems for the action of the solar radiation;
- heat loss coefficient (K), expressed in kWh/K, commonly known as "building's energy constant",reflects its true energy performance, integrating user behavior, as well as allowing the evaluation of thermal mass influence and, corroborated with the G value, can also highlight the solar contribution; it is determined indirectly, by measurement through correlation between external climatic conditions, external temperature values or number of heating days - as an independent variable - and corresponding energy consumption recorded;
- annual environmental impact,expressed in kg$CO_2$/m$^2$/a, is estimated by the equivalent emission index.

For the analyzed Sibelius Solar house, the values of these aforementioned indicators (Table 1) reveal a high level of thermal insulation, reflected in: a lower annual consumption for heating, absence of shading devices against overheating and higher annual consumption per year for cooling. The Energy Performance Certificate developed on the basis of these indicators, in accordance with Romanian regulations, places the building in Energy Efficiency Class A with a specific annual heating energy consumption of 47.64 kWh/m$^2$a, far below the values obtained for similarly thermally insulated buildings. It should be noted, however, that the projected energy performance level was not reached, i.e. 14.00 kWh/m$^2$a, which allows the building to be classified in the Passive House standard.

The proposed house model, which was developed under the MODELLUS project, aimed at reducing these values by optimizing and diversifying the specific passive design strategies, already used in the Sibelius wood solar design concept.

## 3. Optimized single-family housing model

### *3.1. General concept; passive design strategies*

The detailed house model (sustainable, affordable, cost-effective) represents the optimal architectural and constructive solution selected from a catalogue comprising 10 proposed projects,which was the main objective of Stage II of the MODELLUS project.The selected model has been optimized taking into account several criteria, such as: overall architecture, energy efficiency and environmental impact (Fig. 2).

### *3.2. Functional optimization*

The model optimization process targeted specific aspects regarding the volumetric design, functionality and energy compliance with effects on heating and cooling demand, $CO_2$ emissions and, indirectly, on life cycle behavior, including costs.

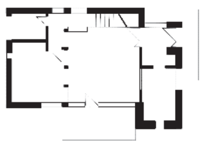
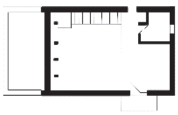
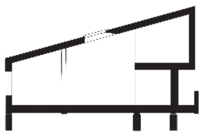
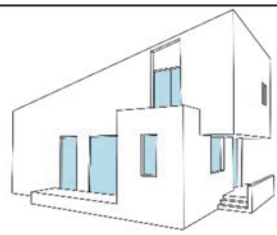
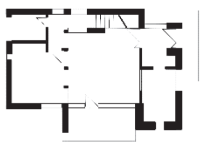
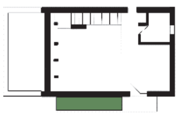
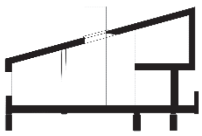
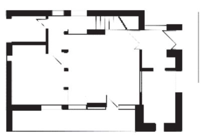
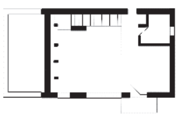
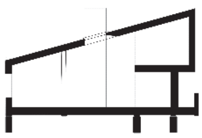
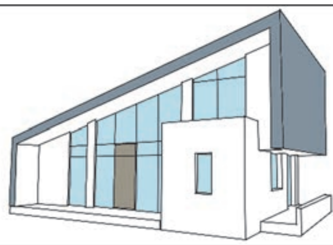
Functional-volumetric optimization for the selected model aimed firstly to meet specific habitation needs for a family of 3 to 4 people and, secondly, to embody a desirable architectural overall image (Table 2). The use of solar passive design elements was also pursued in terms of orientation, glazed surfaces layout, controlled ventilation and compactness ratio. The proposed dwelling has two floors, with an increased air volume (262.65 m$^3$) related to a reduced usable floor surface. This geometry of the interior space allows natural air circulation through the double orientation of windows (North and South).

**Table 1.** Inventory of 1 MJ of steam energy obtained from new and recycled boilers

| *Indicator* | *Performance level* | | | *Determined through* |
|---|---|---|---|---|
| | *Symbol* | *Units* | *Value* | |
| **Global coefficient of thermal insulation** | **G** | W/m$^3$K | 0.454 | calculation |
| **Specific annual energy consumption for heating** | **$q_i$** | kWh/m$^2$ a | 47.64 | calculation |
| **Specific annual energy consumption for cooling** | **$q_r$** | kWh/m$^2$ a | 112.00 | calculation |
| **Heat loss coefficient** | **K** | kWh/K | 10.37 | measurements |
| **Annual environmental impact** | **E $CO_2$** | kg$CO_2$/m$^2$/a | 16.78 | calculation |
| **Solar gains contribution to compensate the heat loss** | - | % | 24.5 | measurements |

**Fig. 2.** Proposed model volumetric perspective

**Table 2.** Functional - volumetric optimization

<table>
<tr><td colspan="4">1. INITIAL MODEL</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>GROUND FLOOR</td><td>UPPER FLOOR</td><td>CROSS SECTION</td><td>VOLUME</td></tr>
<tr><td colspan="4">Of the 10 house model projects developed during the previous MODELLUS phase, was selected the one that best meets the initial project requirements. To this respect, a comparative analysis was conducted considering all energy efficiency factors.</td></tr>
<tr><td colspan="4">2. OPTIMIZED MODEL</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>GROUND FLOOR</td><td>UPPER FLOOR</td><td>CROSS SECTION</td><td>VOLUME</td></tr>
<tr><td colspan="4">The compositional characteristics regarding the spatial-functional organization of the initial model have been preserved for the optimized model, but a series of alterations were made in order to impact positively the energy efficiency: increased south-facing glazed surfaces with protection from excessive sunlight by integrating a green roof, introducing a green wall at ground level, using thermal mass by placing a stone plated fireplace in the center of the house.</td></tr>
<tr><td colspan="4">3. FINAL MODEL</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>GROUND FLOOR</td><td>UPPER FLOOR</td><td>CROSS SECTION</td><td>VOLUME</td></tr>
<tr><td colspan="4">The improved model maintains the internal organization, but several interventions affecting the volumetric composition can be observed: extension of the roof towards South, thus protecting also the glazed surface, use of metal siding as finish layer for two ample vertical planes (NW and SE facades), increased glazed surfaces in relation to the living area, use of a Trombe wall and stone floors for hallways and damp spaces.</td></tr>
</table>

The two bedrooms also have a double orientation: south and north-west for the master bedroom, south and north-west for the children's bedroom, thus improving the quality of the indoor environment (the level of $CO_2$ accumulated during the night, the humidity level of the air) and also regulating the temperature in the warm season by natural ventilation.

### *3.3. Energy and environmental optimization*

To achieve a performance high level in terms of energy efficiency and environmental impact, a series of passive design measures have been proposed. The main objectives were reducing the energy consumption for *heating* and providing the comfort during summer, with a lower energy consumption for *cooling*. Some measures were taken to serve both aforementioned objectives (thermal insulation, glazed surfaces protection) or just one of the two (shading systems, minimizing ventilation rate etc.), thus falling within the category of common or specific measures (Fig. 3).

The proposed measures have been combined in five scenarios, as follows:

**S1 -** The initial solution plus the increase of thermal protection of the envelope elements to an average thermal resistance of 3.77 $m^2K/W$;

**S2** - Scenario **S1** plus integration of reflective surfaces on approx. 50% of the envelope surface;

**S3 -** Scenario **S2** plus optimization of natural ventilation system, differentiated for winter and summer seasons;

**S4** - Scenario **S3** plus the introduction of glazed surface protection systems;

**S5 -** Scenario **S4** plus the introduction of a Trombe wall (greenhouse wall) (Bajc et al., 2015).

The effects of applying different scenarios within the efficiency strategies have been evaluated through numerical simulations using specialized BIM programs, in particular ArchiCAD Eco Design software. The optimal design, characterized by the lowest annual energy demand for heating/cooling and the lowest value of the equivalent $CO_2$ emission index, was achieved by applying a scenario that integrates all the efficiency solutions, including ventilation control for the whole year (variable ventilation, depending on the variation of the outside temperature) (Fig. 4).

The energy and environmental performances obtained from the evaluation of the different scenarios for optimal selection are shown in Table 3.

## 4. Comparative analysis: the Sibelius wood solar house versus the single-family model proposed in Modellus project

The optimized performances of the model, according to the most efficient scenario (**S5**), have been evaluated by numerical simulations using specialized programs (ArchiCAD Eco Design software), the results being presented in Table 4.

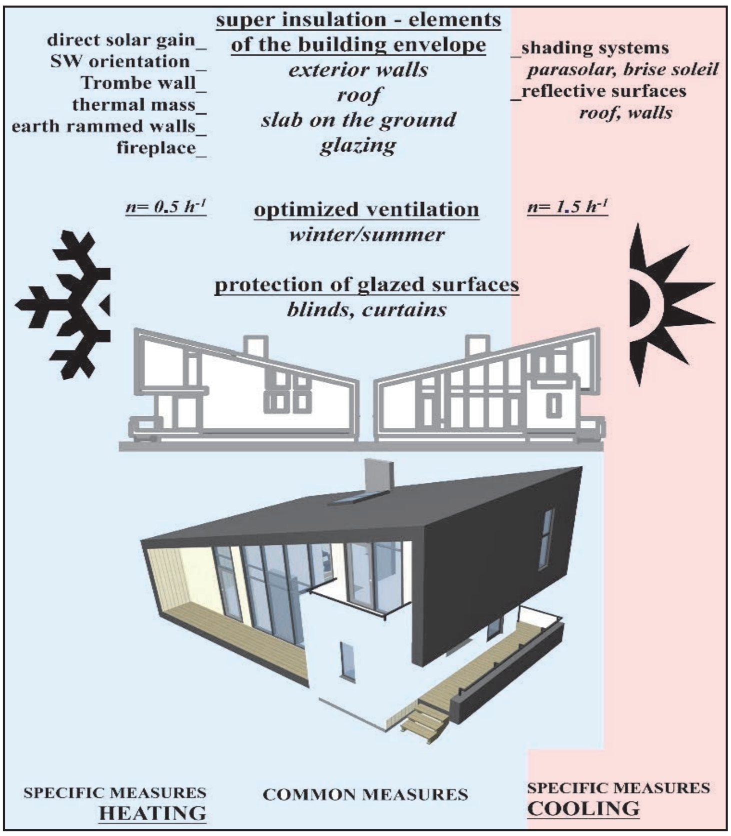



**Fig. 3.** Passive measures for energy and environmental impact optimization integrated into the concept of the proposed model

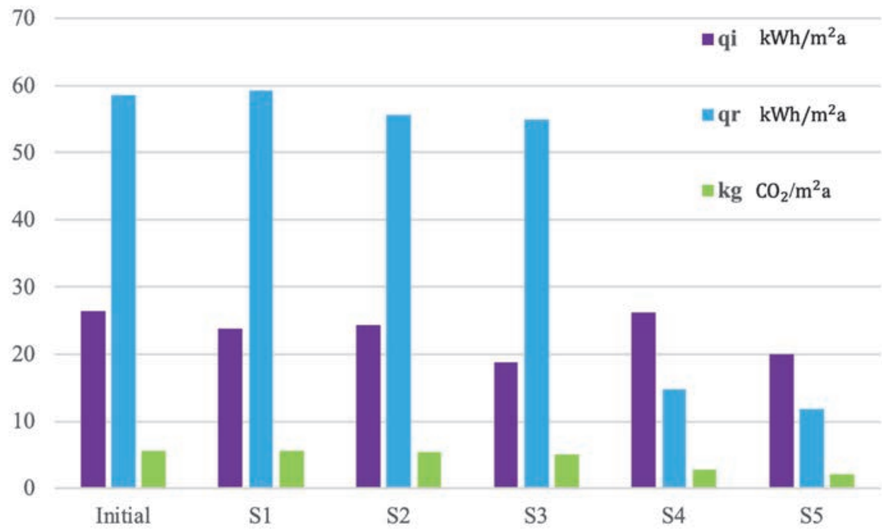



**Fig. 4.** Selecting the optimal scenario in terms of energy efficiency and environmental impact

**Table 3.** Energy performance and environmental impact indicators obtained as a result of applying optimization scenarios

| *Indicator* | *Scenario* | | | | | |
|---|---|---|---|---|---|---|
| | *Initial* | *S1* | *S2* | *S3* | *S4* | *S5* |
| **Specific annual energy consumption for heating ($q_i$) kWh/m$^2$ a** | 26.48 | 23.88 | 24.30 | 18.80 | 26.26 | 19.95 |
| **Specific annual energy consumption for cooling ($q_r$) kWh/m$^2$ a** | 58.59 | 59.20 | 55.55 | 54.97 | 14.87 | 11.9 |
| **Annual impact on the environment, kg$CO_2$/m$^2$/a** | 5.63 | 5.58 | 5.37 | 5.04 | 2.74 | 2.05 |

**Table 4.** Eco-design simulations for the proposed model

| **Project name: Modellus**<br>**City location: Iasi** | | | |
|---|---|---|---|
| Latitude: 47˚9'38" N<br>Longitude: 27˚36'18" E<br>Altitude: 64,00 m<br>Climate Data Source: Strusoft server<br>Evaluation Date: 7 June 2018 | | | |
| ***Indicator*** | | ***Value*** | ***Unit*** |
| **Gross Floor Area** | | 97.075 | m$^2$ |
| **Treated Floor Area** | | 79.777 | m$^2$ |
| **External Envelope Area** | | 221.725 | m$^2$ |
| **Ventilated Volume** | | 262.642 | m$^2$ |
| **Glazing Ratio** | | 16 | % |
| **Building Shell Performance Data** | | | |
| **Infiltration at 50Pa** | | 0.29 | ACH |
| **Thermal Resistances** | **Building Shell Average** | 3.77 | m$^2$K/W |
| | **Floors** | 8.61-8.49 | m$^2$K/W |
| | **External** | 8.61-2.50 | m$^2$K/W |
| | **Openings** | 1.42-1.09 | m$^2$K/W |
| **Specific Annual Values** | **Net Heating Energy** | 23.69 | kWh/m$^2$ a |
| | **Net Cooling Energy** | 16.47 | kWh/m$^2$ a |
| | **Total Net Energy** | 40.16 | kWh/m$^2$ a |
| | **Energy Consumption** | 44.54 | kWh/m$^2$ a |
| | **Fuel Consumption** | 33.85 | kWh/m$^2$ a |
| | **Primary Energy** | 81.16 | kWh/m$^2$ a |
| | **Fuel Cost** | 10.19 | Ron/m$^2$ a |
| | **$CO_2$ Emission** | 2.79 | Kg/m$^2$ a |

The analysis of the yearly distribution of heat losses and free gains (Fig. 5) shows the significant quota of solar inputs, which during the transition months almost compensates completely for heat losses, a result that demonstrates both the efficiency of passive systems for solar energy utilization as well as thermal protection efficiency. Analyzing the values of the energy and environmental indicators for the

Sibelius Wooden Solar House and the model developed within the MODELLUS project, we conclude that the main objectives have been achieved. Thus, the heating / cooling energy demand is reduced by more than 50%, the equivalent $CO_2$ emission value is reduced by 8 times and the contribution of solar inputs to compensate for heat loss is approximatly 2 times higher. In relation to the increase of the global coefficient of thermal insulation (**0.42**) we note that the increase in specific annual energy consumtion for heating is slightly higher (**0.52**) (Table 5).

This can be atributted to the passive measures undertook in the design process. The living room benefits from an extensive south-facing glazed surface protected by a large roof eaves, that allows passive heating during winter (corroborated with an optimisation of solar gains through the Trombe wall solution) and allows for shading during summer. The proposed model has registered an important solar gain contribution to heat loss compensation (more than 50%) and a much lower level of $CO_2$ emissions than the Sibelius House. This is also due to the fact that, for the proposed model, pellets are used for fuel, not gas, as is the case of Sibelius house.

The values obtained by simulation for both the net heating energy and net cooling energy are improoved by adding the Trombe Wall coefficient. Thus, the final values for the Modellus project have been reduced by use of passive design strategies, the Trombe Wall component offering an increase in solar gains throughout the year.

## 5. Conclusions

The results of the detailed analysis of the *Sibelius solar house* in terms of energy consumption and the extent to which comfort conditions are ensured highlight the important role of integrating passive solar energy systems associated with a higher thermal insulation level.

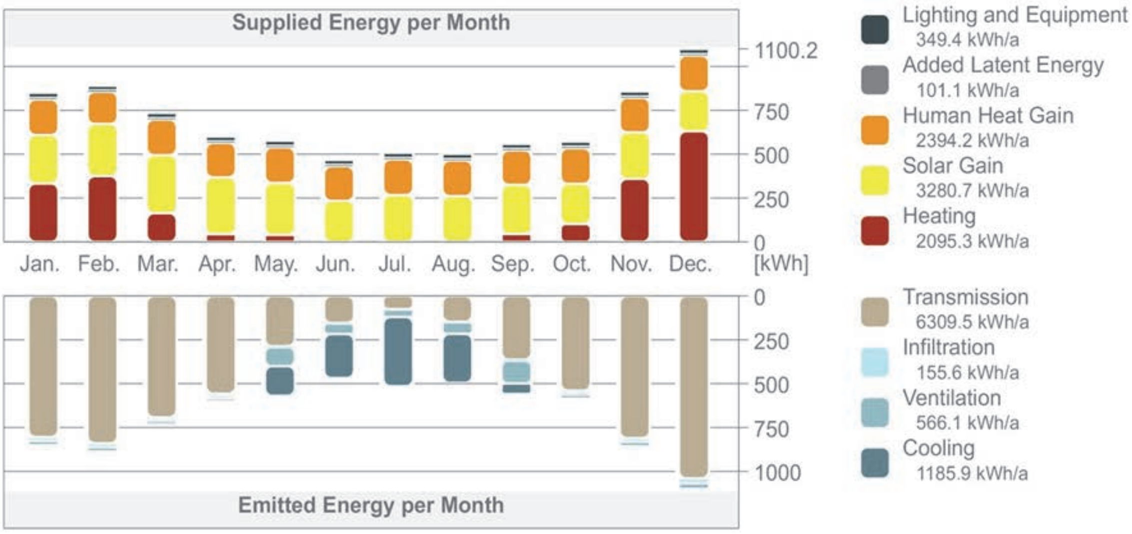
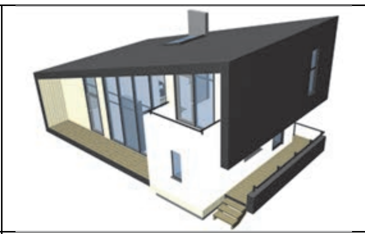



**Fig. 5.** Annual energy balance obtained by numerical simulation

**Table 5.** Comparative analysis: Modellus project / Sibelius house

|  |  | Values obtained through measurements / numerical simulations | |
|---|---|---|---|
| **Sibelius house, S** | **Modellus project, M** | **M/S** | **INDICATORS** |
| **47.64** | **19.95** | **0.42** | Specific annual energy consumption for heating **$q_i$ [kWh/m$^2$a]** |
| **22.6** | **11.9** | **0.52** | Specific annual energy consumption for cooling **$q_i$ [kWh/m$^2$a]** |
| **24.5** | **48.3** | **1.97** | Contribution of solar inputs compensating heat loss **$Q_s/Q_t$ [%]** |
| **16.78** | **2.05** | **0.12** | Annual impact on the environment **$E_{CO2}$ [kgCO$_2$/m$^2$a]** |

In order to achieve the performances required by the NZEB standard, some additional measures are needed, such as: increase of thermal inertia level, introduction of glazing protection systems etc.

The sustainable, optimized single-family house model within the *III^rd^ phase of the MODELLUS project*, detailed at the technical project level, was based on 1 of the 10 models included in the *Sustainable Architecture Solutions Catalogue,* that was the main objective of *Stage II of the MODELLUS project*. The optimization process aimed at reducing the demand for energy from non-renewable heating / cooling sources and the equivalent $CO_2$ emission index. Therefore, has been developed a single-family house project that integrates sustainable architectural and construction solutions and has performance levels superior to those of *Sibelius solar house* (the technology provided by the economic agent).

The implementation of the *MODELLUS* single-family house model would have a positive impact in the following areas:

- *Economic:*

- increasing the competitiveness on the housing market by launching a comfortable, cost-efficient, cost-efficient house prototype;

- the reduction of the primary energy requirement for the operation of the building to about 50% of the value evaluated at the building that constitutes the technology of the economic agent, which by multiplication leads to significant savings of non-regenerative resources;

- exploiting local materials (wood, stone, earth, wool), with a significant investment cost;

- *Environmental impact and adaptability of buildings to climate change:*

- an aproximate 8 times reduction of the level of greenhouse gas ($CO_2$) emissions in the atmosphere over the lifetime of the building compared to the Sibelius Solar House;

- the reduction of the energy embedded in materials, the energy consumed in the execution and exploitation; only replacing the concrete ground slab with a wooden one leads to a 33% reduction in the total amount of energy embedded;

- reduction of cooling demand by 48% through: natural ventilation system design, glazed surface protection and the use of reflective exterior finishes to ensure optimal summer comfort conditions.

- *Social:*

- the possibility of achieving an affordable ecological house with low investment and operation costs;

- capitalizing on local resources and techniques leading to an increase in the supply of jobs;

- *Educational:*

- promoting at large the idea that quality architecture that ensures optimal living conditions does not necessarily imply significant costs.

The model house presented in this research has been evaluated through numerical simulations on a very detailed level as opposed to the existing house where measurements have been performed in situ. The team is determined to build a house prototype based on this project and comparisons between virtual simulations and real measurements will constitute the topic of further research.

**Acknowledgements**
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## References

Bajc T., Todorovic M.N., Svorcan J., (2015), CFD analyses for passive house with Trombe wall and impact to energy demand, *Energy and Buildings*, **98**, 39-44.

Chastas P., Theodosiou T., Bikas D., (2016), Embodied energy in residential buildings-towards the nearly zero energy building: A literature review, *Building and Environment*, **105**, 267-282.

DeKay M., Brown G.Z., (2014), *Sun, Wind and Light, Architectural Design Strategies*, 3rd Edition, Wiley, USA.

EU Directive 31, (2010), Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, *Official Journal of the European Union,* **L153**, 13-35.

Hopfe C.J., McLeod R.S., (2015), *The Passivhaus Designer's Manual: A Technical Guide to Low and Zero Energy Buildings*, Routledge, Taylor and Francis, USA.

Kadhim-Abid A.L., Ichim P., Atanasiu G.M., (2019), Seasonal occurrence of heat island phenomenon in the urban built environment, *Environmental Engineering and Management Journal*, **18**, 417-424.

Obergassel W., Arens C., Hermville L., Kreibich L., Hersmann F., Ott H.E., Wang-Helmreich H., (2015), Phoenix from the ashes: an analysis of the Paris Agreement to the United Nations Framework Convention on Climate Change – Part I, *Environmental Law & Management Published By Lawtext Publishing Limited*, **27**, 243-262.

Santamouris M., (2006), *Environmental Design of Urban Buildings, an Integrated Approach*, Taylor and Francis, USA.

Secu A., Romila C., (2014), Simplified calculation of the global thermal insulation coefficient, *The Bulletin of the Polytechnic Institute of Jassy. Constructions. Architecture Section*, **LX (LXIV)**, 67-77.

Thomas R., (2006), *Environmental Design. An Introduction to Architects and Engineers*, Taylor and Francis, USA.

Vais D., (2009), From house to "residence". Peripheral growth in post-socialist Cluj (Romania), *Studia Universitatis Babes-Bolyai - Sociologia*, **1**, 57-78.