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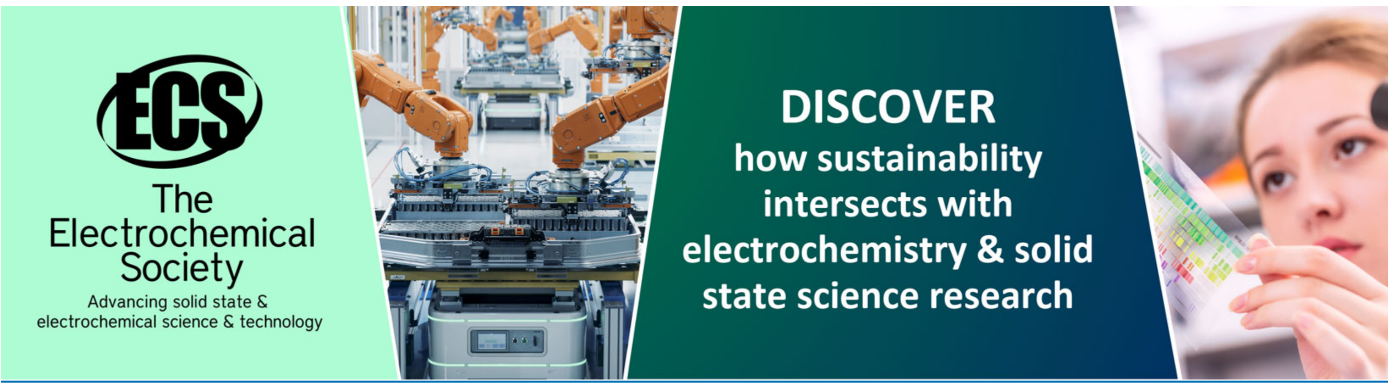

Environmental and Economic Sustainability Indicators for External Walls

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Abstract. The current context of the intensification of climate changes, on one hand, and the sharp increase in prices in the buildings sector, on the other, impose the need to find solutions that considers both economic and environmental protection aspects.

This paper proposes a method of evaluating the solutions most often used today in Romania for the exterior walls in single-family residential buildings based on a global index that takes into account both environmental performances (adjusted thermal resistance, carbon footprint) as well as the economic ones (costs).

1. Introduction

The improvement of living conditions due to technological advances in recent years has led to a better life for mankind, but most of these advances are based on technologies that do not take into account the possibility of environmental degradation during their use, a fact that has led to adverse climate change. Buildings and infrastructure are major contributors to global warming. The construction sector is responsible for 40% of the total energy consumption and 36% of the greenhouse gases emitted at the level of the European Union [1].

The heat loss through the external walls represents a very significant percentage of the total heat loss of a building, namely 35% for buildings with ground floor level and 65% for buildings with several levels [2]. That is why it was considered relevant to investigate the effect of adopting different types of solutions for the opaque part of building facades.

Thus, the following types of walls were considered, from the point of view of economic and environmental sustainability, for a single-family residential building with ground floor:

- external closing walls with a metallic frame type structure;
- external closing walls with frame-type structure made of softwood;
- external closing walls with a confined masonry structure made of ceramic hollow bricks (with vertical cores);
- external closing walls with a confined masonry structure made of autoclaved aerated concrete (AAC).

The elements taken into account from the point of view of environmental sustainability were:

- unidirectional specific thermal resistance R [m²K/W];
- mean adjusted thermal resistance R' [m²K/W];
- carbon footprint for the production of the construction materials used [kg CO_2 eq/m²].

Considering economic sustainability, a price was calculated for a representative area of approximately fifteen square meters of wall.

Then, a global index that takes into account both environmental and economic sustainability performances was developed and tested. Previously conducted research focused on evaluating building materials [3] – [5] or even entire buildings [6], [7] using combined sustainability criteria to obtain a more holistic approach.

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2. Methods

The study consists in the analysis, from the point of view of sustainability in terms of environmental protection and financial aspects, of some solutions of external closing walls for different structure types used on a large scale in Romania, for dwellings with ground floor.

Thus, a simple dwelling plan (figure 1) was considered (to make it easier to follow the purpose of the work by enabling simpler calculations), but which would offer at least the minimum comfort level required by the NP57/2002 Normative. The level height was considered 2.80 m.

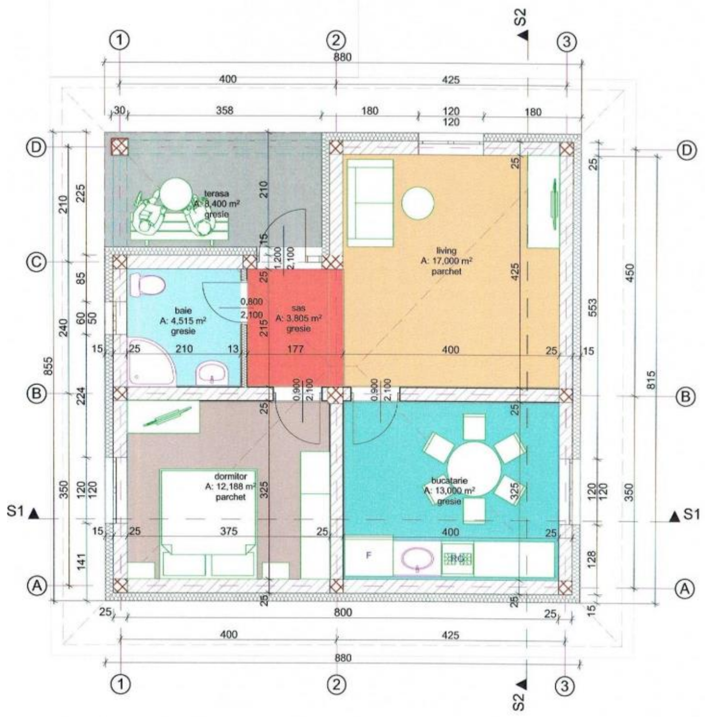


Figure 1. The ground floor plan for the analysed building.

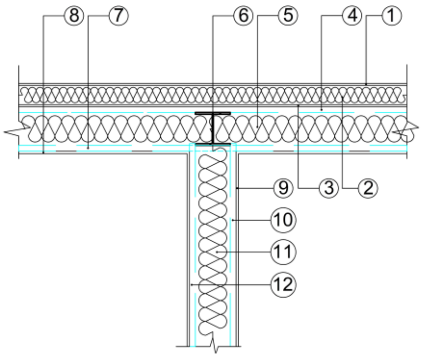
The four solutions of the composition of the external walls analysed in this study were:

a. Metallic frames

In the case of the solution with a frame-type structure made of metallic profiles, a calculation was made to determine the types of profiles required, taking into account the provisions of the P100-1/2013 and Eurocode 3 regulations. For the calculation of the seismic force, a site characterized by the design ground acceleration, ag=0.25g and a corner period Tc=0.7s was considered. Thus, a HEA 180 metallic profile was established for columns.

A detail was considered for an exterior closing and interior partitioning wall to allow a specific finishing system for dwellings (washable lime on the inside and decorative plaster on the outside). The use of closing elements generally used for structures with metallic profiles, namely prefabricated sandwich panels, specific to industrial units, was avoided. It was adopted a system in which on the columns are welded metallic profiles TP30x30x3 type, which will represent the support for the oriented strand boards (OSB) boards on the outside and for the gypsum-cardboard boards on the inside (figure 2). A thermosystem can be applied over the OSB boards on the outside, which can be finished with decorative plaster, and the plasterboard boards on the inside can be finished with washable lime.

In the case of metallic frames, the openings were bordered by TP 30x30x3 profiles. These details were taken into account in the economic evaluation.



1 - decorative plaster 10 mm
2 - expanded polystyrene 100 mm
3 - OSB board 10 mm
4 - metallic profile TP 30x30x3 / 1000 mm
5 - mineral wool 170 mm
6 - metallic profile HEA 180
7 - metallic profile TP 30x30x3 / 1000 mm
8 - gypsum cardboard 12 mm
9 - gypsum cardboard 12 mm
10-metallic profile TP 30x30x3 / 1000 mm
11-mineral wool 180 mm
12-metallic profile TP 30x30x3 / 1000 mm

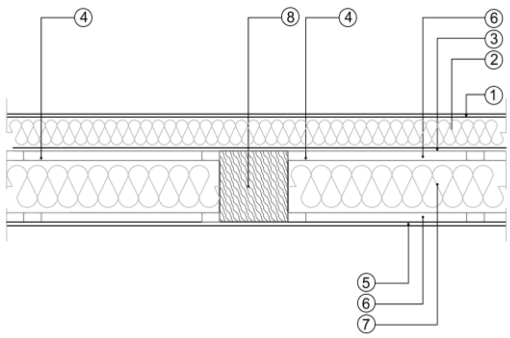
Figure 2. Detail of the exterior and interior wall – metal frames solution.

b. Softwood timber frames

The AxisVM software [8] was used to determine the necessary sections of the elements for the softwood frames, in compliance with the prescriptions of NP 005-2022 and SR EN 1995-1-1:2004. It was found that a section of the wooden columns approximately equal to that of the columns of metal profiles would not have been enough, so it was decided to increase the number of frames in this structural solution (where the architectural solution allowed this) so that the thickness of the walls results about the same. Thus, it was possible to use a 170 mm thermal insulation on the inside of the wall - the same thickness as in the case of the metallic frame structure.

The aim was to provide the two solutions with roughly the same unidirectional thermal resistance, with thermal bridges of comparable size, so that the results of this study would be as accurate as possible.

In order to determine the sequence of layers inside the wall, it was tried a similarity between this solution and the one with metallic profile frames. The softwood frames will be plated externally with 10 mm OSB boards and internally with 12 mm plasterboard boards (figure 3). The plane rigidity of the wall will be ensured both by the OSB boards on the outside and by the arrangement of bracing at the intersections between the columns and beams, respectively columns and fixing base slab, a fact taken into account in the financial evaluation. For plating with OSB plates or plaster-cardboard, a grid of metallic profiles type CW 60x0.45 or UV 30x0.45 was used as a support.



1-decorative plaster 10 mm
2-expanded polystyrene 100 mm
3-OSB boards 10 mm
4-metallic profile CD 60x0.45 mm
5-gypsum cardboard 12 mm
6-unventilated air (in the area of the perimetral metallic profile UD30x0.45 mm)
7-mineral wool 170 mm
8-softwood timber column C22 230x230 mm

Figure 3. Detail of the exterior wall – wood frames solution.

c. Hollow brick confined masonry

In this case, the structural system was made taking into account the minimum constructive details imposed by P100-1/2013 and CR6-2013, for a confined masonry that ensures a takeover of gravitational and seismic loads. The relatively small spans (maximum interaxial dimension of 4.5 m) and the height level (ground floor) were taken into consideration.

For masonry solution, a widely used brick, namely ceramic brick with vertical holes with plan dimensions of 240x290x188mm and a mortar of M5 class, was considered. The C20/25 class reinforced concrete cores are provided at all wall intersections and for the reinforced concrete wall beams. Reinforced concrete lintels, C20/25 concrete class, were provided over the openings. The lintel height is equal to the brick height and the length exceeds the opening by 45 cm on each side (figure 4).

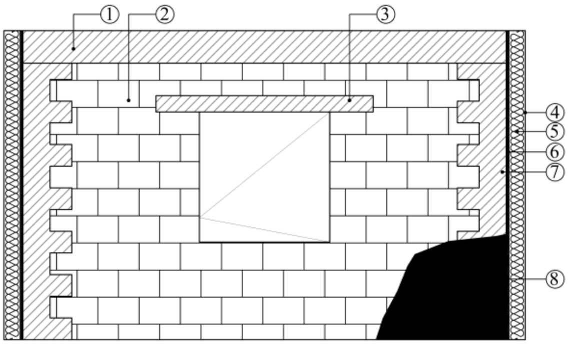


Figure 4. Detail of the exterior wall – confined masonry solution.

d. Autoclaved aerated concrete (AAC) block confined masonry

For this solution, the same constructive details were adopted as in the case of masonry with ceramic brick with vertical holes.

According to the provisions imposed by P100-1/2013 and CR6-2013, for the structural walls of the analysed building (dwelling on the ground floor, located in an area characterized by an acceleration of the ground ag≤0.25g) can be used AAC block with standardized unit compressive strength f_b=3.5N/mm^2 and f_b=5N/mm^2 and M5 brand mortar.

Table 1 shows the calculated thermotechnical characteristics of the used materials, according to Normative C107/1-2005, annex A.

Table 1. Thermal characteristics of materials.

Material	Apparent density ρ [kg/m^3]	Thermal conductivity λ [W/mK]	Mass caloric capacity c [J/kgK]
Metal	7850	58	480
Decorative plaster	1600	0.87	840
Reinforced concrete	2500	1.74	840
Mortar	1700	0.87	840
Brickwork	1700	0.75	870
Expanded polystyrene	20	0.04	1460
OSB boards	600	0.17	2510
Mineral wool	60	0.04	750
Gypsum cardboard	1000	0.37	840
Pine, fir wood	550	0.17	2510
AAC block masonry	750	0.28	840

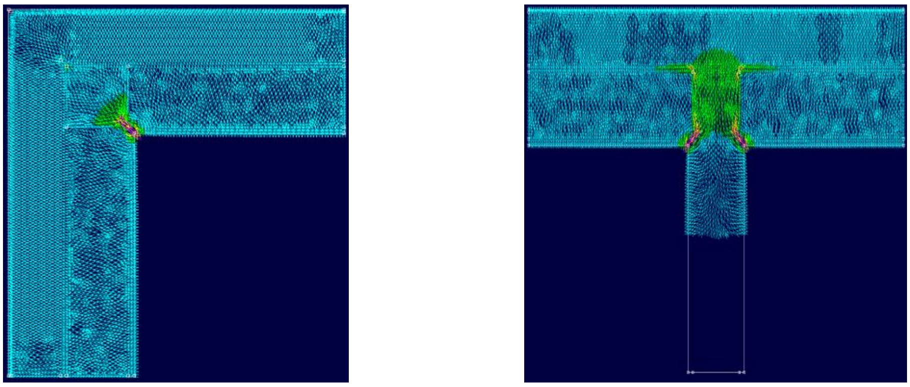
Based on the thicknesses values of the material layers presented in figures 2-4 and the standard thermal conductivities in table 1, the unidirectional specific thermal resistances were calculated for all four external wall solutions considered.

For the calculation of the adjusted specific thermal resistances, values of the linear thermal transmittances determined after modelling the thermal field with the help of the RDM7 calculation program were used [9]. According to C107/3-2005, the calculation relationship is:

$$\psi = \frac{\Phi}{\Delta T} = -\frac{B}{R} \tag{1}$$

where: ψ is the linear thermal transmittance, [W/mK];
Φ is the thermal flow, [W/m];
ΔT is the temperature difference between indoor and outdoor, [K];
B is the width of the analyzed domain, [m];
R is the specific unidirectional thermal resistance, [m^2K/W].

In figure 5 is exemplified the allure of the heat flow density in the case of thermal bridges of the "external corner" and "intersection exterior wall - interior wall" type for solution 4 (AAC block confined masonry).



a b

Figure 5. Specific heat flows resulted from thermal bridge modelling: a) external corner; b) T-joint intersection.

There were considered the thermal transmittance values for the following types of thermal bridges: external corner, internal corner, T-joint intersection, intersection of the external wall with the concrete slab on the ground, intersection of the external wall with the upper floor, window and door frame joint. The lengths of the thermal bridges were established according to the information from figure 1. Thus, the adjusted specific thermal resistances related to the four opaque external walls (Northern, Southern, Eastern, and Western façade, respectively) were determined and then the mean adjusted specific thermal resistance of all external walls was calculated.

The carbon footprint expressed in kg CO_2 eq./m^2 was calculated using the UBAKUS software [10], based on the thicknesses of the material layers shown in figures 2-4 and the characteristics of the materials shown in table 1. Figure 6 shows the result obtained in the solution 4 (AAC block confined masonry). Both the embodied primary energy (from non-renewable sources) and greenhouse gas emissions are highlighted, total values and for each individual component material.

For the financial evaluation, the wall in axis D between axes 2 and 3 was considered to be representative, it having an area of 14 m^2, which represents approximately 15% of the total area of the external walls and also containing a carpentry opening for which, depending on each structural system analyzed, additional structural compensation measures must be provided. These constructive solutions were described for each solution separately and were included in the calculation of the quantities that formed the basis of the economic evaluation. The values presented are in RON (Romanian leu), do not include VAT, and the prices are at the level of February-March 2022.

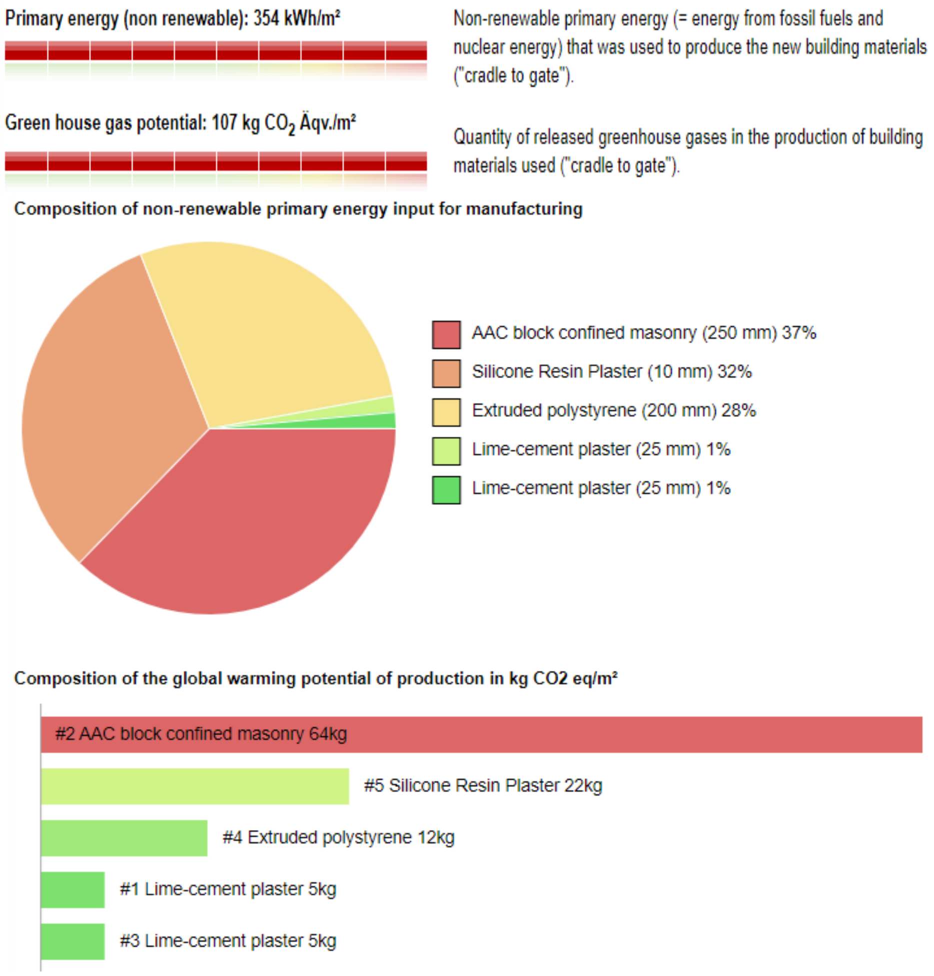


Figure 6. Embodied primary energy and carbon footprint for solution 4.

3. Results and discussions

The results of the calculation of the environmental performance indicators (adjusted specific thermal resistance, embodied primary energy, carbon footprint) and economic performance (costs) are presented in table 2, for all four solutions adopted for the external walls of the studied building.

Table 2. Environmental and economic performance indicators for external walls.

Solution	1-Metallic frames	2-Wood frames	3-Hollow brick masonry	4-AAC block masonry
R [m^2K/W]	7.385	6.872	5.569	6.128
R'_{North} [m^2K/W]	3.239	3.152	2.896	3.069
R'_{South} [m^2K/W]	3.805	3.686	3.341	3.572
R'_{East} [m^2K/W]	3.491	3.390	3.094	3.291
R'_{West} [m^2K/W]	3.384	3.288	3.009	3.195
R'_{mean} [m^2K/W]	3.48	3.38	3.09	3.28
Primary energy [kWh/m^2]	480.1	396	387	354
Carbon footprint [kg CO_2 eq./m^2]	109.35	84	80	107
Costs [RON]	7548	6823	5220	5135

As can be seen from the values given in table 2, the highest value of the unidirectional specific thermal resistance R is in the case of the metallic profile structure, and the lowest is in the case of the hollow brick masonry. A 170 mm layer of mineral wool was placed inside the walls, in the case of the metallic structure and in the case of the wooden frame structure, due to the width of wall related to the dimensioning of the wooden columns. Supplementary, a layer of 10 cm expanded polystyrene was placed on the outside part as an external thermal insulation system. The presence of the two layers of thermal insulation, internal and external, leads to positioning the mentioned solutions on the top two. Taking this into account, in order to increase the accuracy of the study results, for the two solutions with load-bearing masonry type structure was considered a thermal system with a 20 cm of expanded polystyrene on the outside.

It can be noticed that following the calculation that takes into account the influence of thermal bridges, the "ranking" remains unchanged compared to the one in the case of the unidirectional specific thermal resistance R, but the relative difference between the most efficient solution and the least efficient solution, decreased by about 2 times.

Regarding the carbon footprint, the best results are given by the solution with wooden frames and the solution with confined brickwork made of fired clay ceramic brick. Also, a rather large difference can be noticed between the solutions with metallic profiles and AAC block masonry and the other two solutions taken into account.

Concerning the economic performance, it is observed that the most expensive solution is the metallic frames solution, while the solutions based on load-bearing masonry made of AAC block or ceramic brick prove to be more efficient from a financial point of view.

An explanation of this situation would be given by the recent exponential increase in the prices of metal products used in construction, while for ceramic brick, the raw material being more accessible (clay quarries generally located at a short distance from the factory), price increases were much lower.

In order to establish a ranking of the debated solutions taking into account both environmental and economic performance, the following method was proposed:

- the values of the environmental and economic indicators related to each solution were compared with the reference values, resulting in a certain degree of compliance of the criteria taken into account;
- this degree of compliance of the criteria was associated with an importance coefficient, thus resulting in some values that led to the possibility of creating a ranking of the analysed solutions.

Thus, the results obtained for the indicators related to mean adjusted specific thermal resistance, carbon footprint and costs were reported to a series of reference values, as follows:

- Reference R'_{mean} = 4.00 m^2K/W;
- Reference carbon footprint = 75 kg CO_2 eq./m^2;
- Reference cost = 5,000 RON.

The degree of compliance of the imposed requirements was represented graphically in figures 7-9.

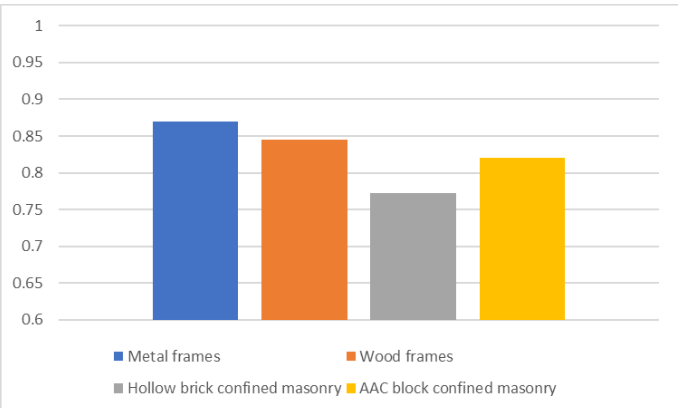


Figure 7. The degree of compliance with the reference R'_{mean} value [m^2K/W].

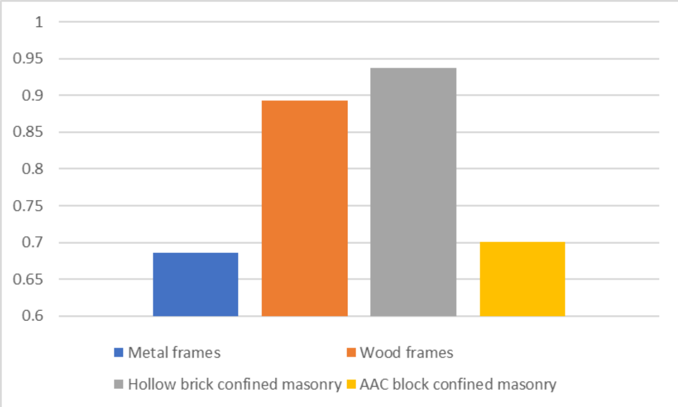


Figure 8. The degree of compliance with the reference carbon footprint value [kg CO_2 eq./m^2].

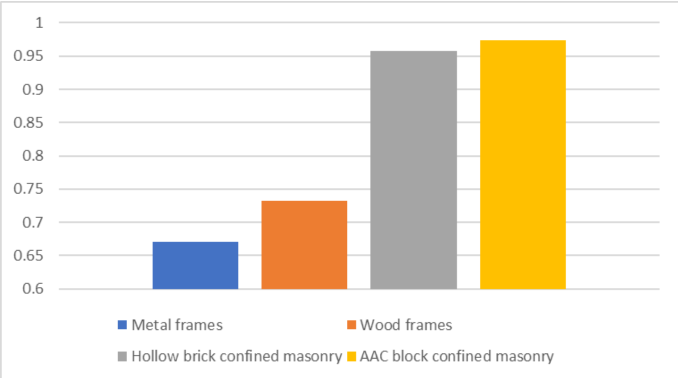


Figure 9. The degree of compliance with the reference costs value [RON].

Figure 10 shows a ranking of the solutions for a score in which the coefficient of importance with a higher value (0.4) was given to the "price" criterion, and the indicators related to environmental protection had equal coefficients of importance (0.3), but lower than the price-related one. It can be seen that the solutions that use confined masonry are ranked in the first two positions, the next position is for the solution with wooden frames, and the solution with metal profile frames is in fourth position. Using these importance coefficients, the scores accumulated by the four solutions are not far apart. Practically, the maximum difference between the analysed solutions is 1.64 points for a score from 1 to 10.

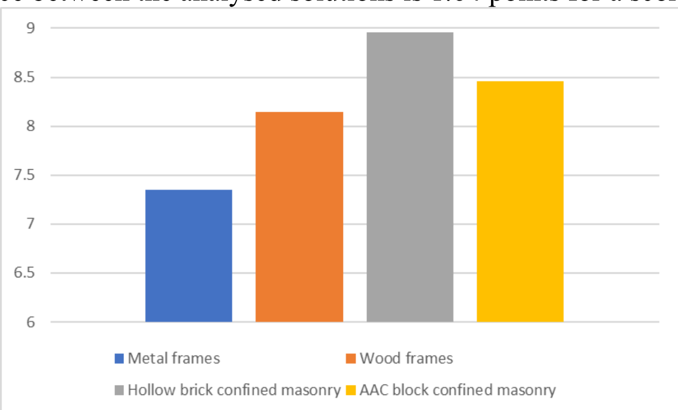


Figure 10. Ranking according to the degree of compliance of the reference values with relationship ($0.3*R_{mean}'+0.3*$carbon footprint$+0.4*$cost$)*10$ (points).

This can lead to the conclusion that on a ranking based more on cost, the four debated solutions do not present major differences, but the solutions that assume confined masonry, for the types of walls considered, represent a (slightly) more efficient solution (under the conditions of prices shown above). Also, there is a small difference between the points accumulated by the solution with masonry confined with AAC blocks and the solution with wooden frames (the solutions on position 2 and position 3, respectively). Taking into account the major restrictions for AAC blocks masonry from P100-1/2013 and from CR6/2013, it can be concluded that the most effective solution (for zones characterized by a ground acceleration, ag≥0.25g and in the price conditions presented above) remains the "classic" one of confined masonry, with burnt clay bricks, followed by the solution with a wooden frame structure.

Figure 11 shows a ranking of the solutions that take into account the impact on the environment, more than the financial impact. It can be seen that the environmental indicators (R'_{mean}, carbon footprint) were given a higher importance coefficient (0.4) than the cost indicator (0.2).

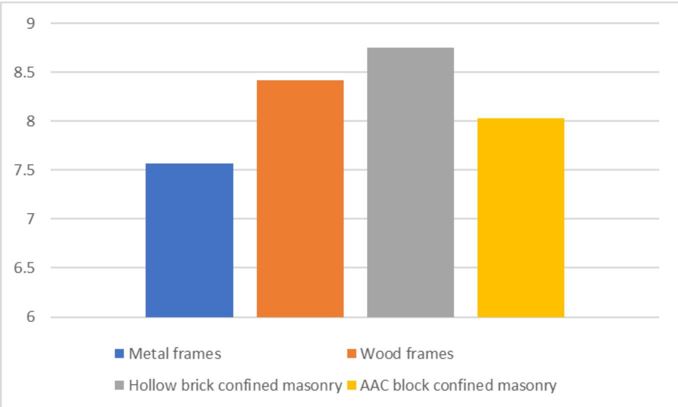


Figure 11. Ranking according to the degree of compliance of the reference values with relationship ($0.4*R_{mean}'+0.4*$carbon footprint$+0.2*$cost$)*10$ (points).

In this case, the ranking has changed as follows: in the first two positions, there are the solutions with hollow brick confined masonry and wood frames and, in the 3rd position, but with a little difference, there is the structure of the AAC block confined masonry. On the 4th position is the solution with metal frames.

It can be seen that on a ranking based predominantly on the indicators related to environmental protection, the difference between the score for the solution with wood frames (from the 2nd position) and that with confined masonry made of AAC blocks (from the 3rd position) has increased, compared to the situation in the case of the ranking based predominantly on price.

In this case, the score difference between the solution in the first position and that in the last position is smaller than in the previous ranking, namely 1.24 points for a score from 1 to 10.

4. Conclusions

The current situation on the construction market (in the context of the chaotic increase in prices and the lack of continuity of supply with certain materials but also the need to apply environmentally friendly solutions), requires a work supported by research to compare existing solutions and to innovate new solutions.

This paper presented a comparative analysis of some existing solutions on the market, for the walls of dwellings with one height level. Some of these solutions are used on a larger scale (AAC block masonry, ceramic brickwork or wooden frames), others at a smaller scale (metallic profiles frames). The aim of the paper was to identify the best solutions, by comparing the performance of each, in relation to standard indicators of economic and environmental sustainability.

As a general conclusion of the present study, it could be stated that, taking into account the considered environmental and economic sustainability indicators, the solution "confined masonry with ceramic bricks" is the most effective, being closely followed by the solution "frames made of resinous wood".

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