Chapter

Technical-Economic Research for Passive Buildings

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Abstract

The Energy Performance of Buildings Directive (EPBD) 61 requires all new public buildings to become near-zero-energy buildings by 2019 which will be extended to all new buildings by 2021. This concept involves sustainable, high-quality, valuable, healthy and durable construction. Foundation, walls and roofs are the most essential elements of a house. The type of foundation for a private house is selected considering many factors. The article examines technological and structural solutions for passive building foundation, walls and roofs. The technical-economic comparison of the main structures of a passive house revealed that it is cheaper to install an adequately designed concrete slab foundation than to build strip or pile foundation and the floor separately. Timber stud walls are the cheapest wall option for a passive house and 45–51% cheaper than other options. The comparison of roofs and ceilings showed that insulation of the ceiling is 25% more efficient than insulation of the roof. The comparison of the main envelope element efficiency by multiple-criteria evaluation methods showed that it is economically feasible to install concrete slab on ground foundation, stud walls with sheet cladding and a pitched roof with insulated ceiling.

Keywords: passive house, foundation, walls, roof, technological solutions, multiple-criteria evaluation

1. Introduction

A passive house is not a new method of construction. It differs from ordinary houses by good thermal insulation, high-quality windows and heat recovery ventilation system. All these features lead to the lower demand for thermal energy. The Energy Performance of Buildings Directive (EPBD) 61 requires all new public buildings to become near-zero-energy buildings by 2019 which will be extended to all new buildings by 2021 [1]. A passive house becomes a standard for energy-efficient buildings [2]. The problem in modelling a passive house occurs when investment into construction is estimated and the payback period for investment is calculated. The payback period depends on thermal energy price, which is difficult to forecast. Therefore a house of lower energy efficiency class is a less risky investment for an individual builder [3–5].

A passive house is the building with very low energy demand and uses only one-fourth or even less energy compared to the conventional buildings. Usually, passive houses do not have separate heating systems. Regenerative ventilation system is enough. The primary idea of such a house is to reduce the energy demand and at the same time maintain comfortable microclimate inside. The effectiveness of a passive house is based on the efficient thermal insulation and higher tightness of envelope components. A passive house is the concept (method) of construction applied in practice. A passive house is a standard widely used in constructing energy-saving buildings. A newly constructed passive house must save 80% of heat resources; otherwise it is not a passive house. The heating energy demand of a passive building is less than 15 k Wh/m^2 per year. However, a passive house is something more than just an energy-saving house [5–9]. This concept involves sustainable, high-quality, valuable, healthy and durable construction. Features of a passive house are the following: high insulation of envelope components, high-quality windows, good tightness of the building, regenerative ventilation system and elimination of thermal bridges. The recommended architectural solutions are simple forms, less angles in order to avoid the development of thermal bridges at the joints. The most effective form of the house is the one with the smallest area of external walls. For these reasons it is easier to build a house of bigger floor area meeting the passive house criteria because the area of external wall and thermal bridges is smaller than the useful floor area of the building. A passive house should have no basement; otherwise the basement must be well insulated. Besides, it is recommended to plan as many windows on the southern façade in order to use more natural solar energy. Windows must be made of special frames filled with double-chamber selective glass units. The site also has a significant effect on the energy demand by the building. Shadows from the neighbouring buildings must be considered when building a house in the district where tall buildings prevail. Water may be heated by electricity; however solar panels are recommended. Combination solar wind power generation units are recommended to produce electricity for lighting and regenerative systems as well as for household needs [10, 11]. This article examines technological and structural solutions for passive buildings' main structures.

2. Alternative solutions for passive house structures

2.1 Alternative solutions for foundation

Foundation is one of the most essential elements of a house. The type of foundation for a private house is selected considering many factors. The main factors are the type of the ground, groundwater level, frost line in the region, presence or absence of the basement, type of bearing walls, architectural decisions and financial resources. To choose the correct foundation type for the house, the builder must have the results of engineering and geological surveys, the final design of the building and calculations of loads.

2.1.1 Strip foundation

Strip is made of assembled concrete blocks or monolithic concrete. It is built under the bearing walls and partitions. This method requires land excavation, concrete element assembling and concrete pouring work. Construction of strip foundation is not cheap, but it is the most appropriate foundation for a house with a basement.

Monolithic strip foundation provides a more rigid framework, but the installation is longer than the foundation made of assembled concrete blocks. Monolithic strip foundation is recommended when the house is built on expanding soil.

Strip foundation is recommended when the house walls are made of heavier materials, for more than one-storey houses, and there is no need to build other types of foundations (e.g. pile foundation), which is necessary while building a house on weak, expanding or watery soil. Strip foundation is generally selected due to simple construction method, regardless the longer time required to build it.

2.1.2 Pile foundation

Pile foundation distributes the load of the building via pile cap and sides; therefore the stress propagates across the big volume of soil. Pile foundations do not sink much and have a high load-bearing capacity; thus they are suitable for buildings that are sensitive to subsidence.

As the piles are driven deep into the ground, it is impossible to fully insulate the entire foundation. Thermal bridges occur at the pole and grade beam joints, and they deteriorate the heat conservation capacity of the building.

2.1.3 Monolithic slab

A monolithic slab is a one-piece load-bearing foundation structure. Concrete is poured into special polystyrene foam forms that completely isolate the foundation slab from direct contact with the soil. It is the single type of foundation where the load-bearing monolithic slab has no contact with the soil and has the highest thermal resistance value. The thermal resistance value R of this foundation may be as high as 9.7 (R = 9.7 m^2 K/W) and higher. Thus, thermal bridges, frost and foundation deformations are avoided. The monolithic slab bears the load of the building across the entire plane rather than individual segments. The monolithic slab has from 3 to 20 times bigger supporting area than conventional foundations. For this reason it is less susceptible to movement and is firm and stable. All traditional foundation structures create thermal bridges because there are no structural possibilities to avoid them. Monolithic slab is the only exception where the entire concrete slab can be thermally insulated at 100%. A properly installed slab has no thermal bridges, and the main advantage of this foundation is high thermal resistance and tightness.

Estimate calculations of strip, pile and monolithic slab foundations are done. A private two-storey house is selected for the calculation. The calculated foundation area is 110 m^2. Labour, materials, machinery and total costs for foundation installation are calculated.

2.2 Alternative solutions for walls

2.2.1 Timber stud wall with sheet cladding

Double-stud wall structure significantly decreases the formation of thermal bridges and enables to diminish the weight of the entire structure. Thermal insulation layer is installed inside the double stud without an additional frame. The insulation layer thickness may vary depending on the required heat transfer factor U value. Thermal insulation made of PAROC WAS 25t sheets simultaneously serves as a wind barrier. This layer is fixed onto the studs. It is one of the best structures for a passive house (**Figure 1a**). An auxiliary frame on the internal side is required to install a tight vapour insulation, which in this system also serves as an air barrier. The vapour insulation is installed between the auxiliary internal frame and the thermal insulation layer in the middle. For this reason the engineering systems installed in the wall structure will not damage the tightness of the insulation layer. Four hundred and twenty millimetres of thick thermal insulation layer enables to achieve the U value ≤ 0.09 W/(m^2 K) [12].

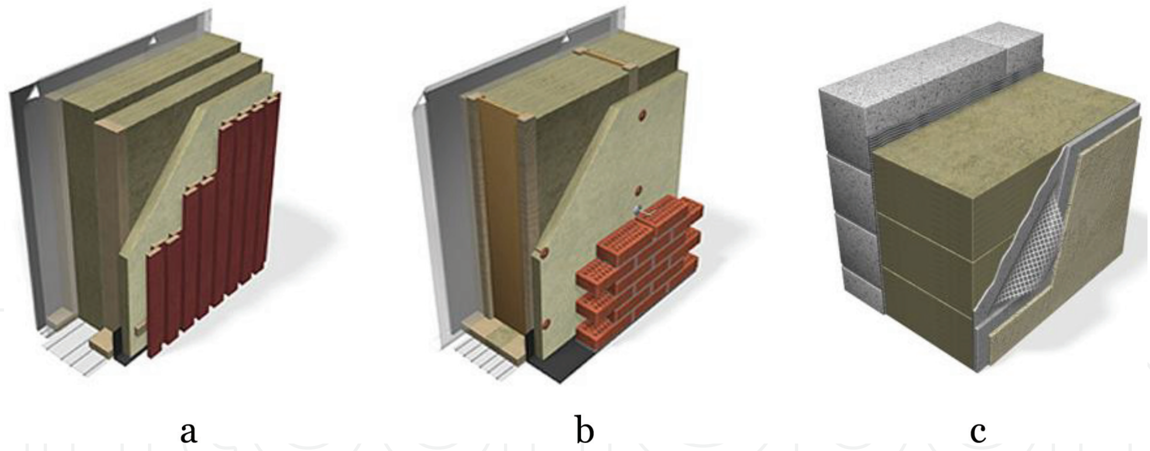

Figure 1.
Structural solutions for walls: (a) timber stud wall with sheet cladding, (b) glued laminated timber I-joist stud wall with brick finishing and (c) plastered silicate block wall.

2.2.2 Glued laminated timber I-joist stud wall with brick finishing

Glued laminated timber (glulam) I-beam frame significantly reduces the impact of thermal bridges on the structure compared to the ordinary stud wall (**Figure 1b**). Thermal insulation made of PAROC WAS 25t sheets simultaneously serves as a wind barrier. This layer is fixed onto the studs. U value is ≤ 0.09 W/(m^2 K) when the thickness of thermal insulation layer is 420 mm [12].

2.2.3 Plastered silicate block wall

For the thermal insulation of plastered façades, the best option is rock wool sheets with vertically oriented fibre structure or special boards for plastered façades. These boards are fixed with adhesives onto the brick or concrete wall. The plates are covered by reinforcing layer and finishing plaster coat. Mineral or silicate decorative plasters should be used for such façades because they have better permeability for water vapour, i.e. create breathing walls (**Figure 1c**).

2.3 Roof and floor alternative solutions

The building of a passive house also involves the choice between a flat and pitched roof. If a pitched roof is selected, then there is a choice between thermal insulation of the roof and insulation of the ceiling with a cold attic. As in the case of walls, additional weight and thickness of roof insulation material must be considered. For the insulation of the entire pitched roof, the rafter height can reach up to 400–500 mm. Composite glulam rafter goes across the entire width of the thermal insulation layer. For the insulation of ceiling, less thermal insulation material is required, and the beam height may be lower; however the spans between beams must be narrower. Ceiling can be insulated not only with sheets but also with bulk insulating materials. In flat roofs the load-bearing structure is made of reinforced concrete slabs. Thermal insulation is installed in several layers with ventilation channels.

2.3.1 Thermal insulation of ceiling with an attic

Thermal insulation is made of three or more layers without any gaps between sheets and by overlapping the joints of the previous row (**Figure 2a** and **b**).

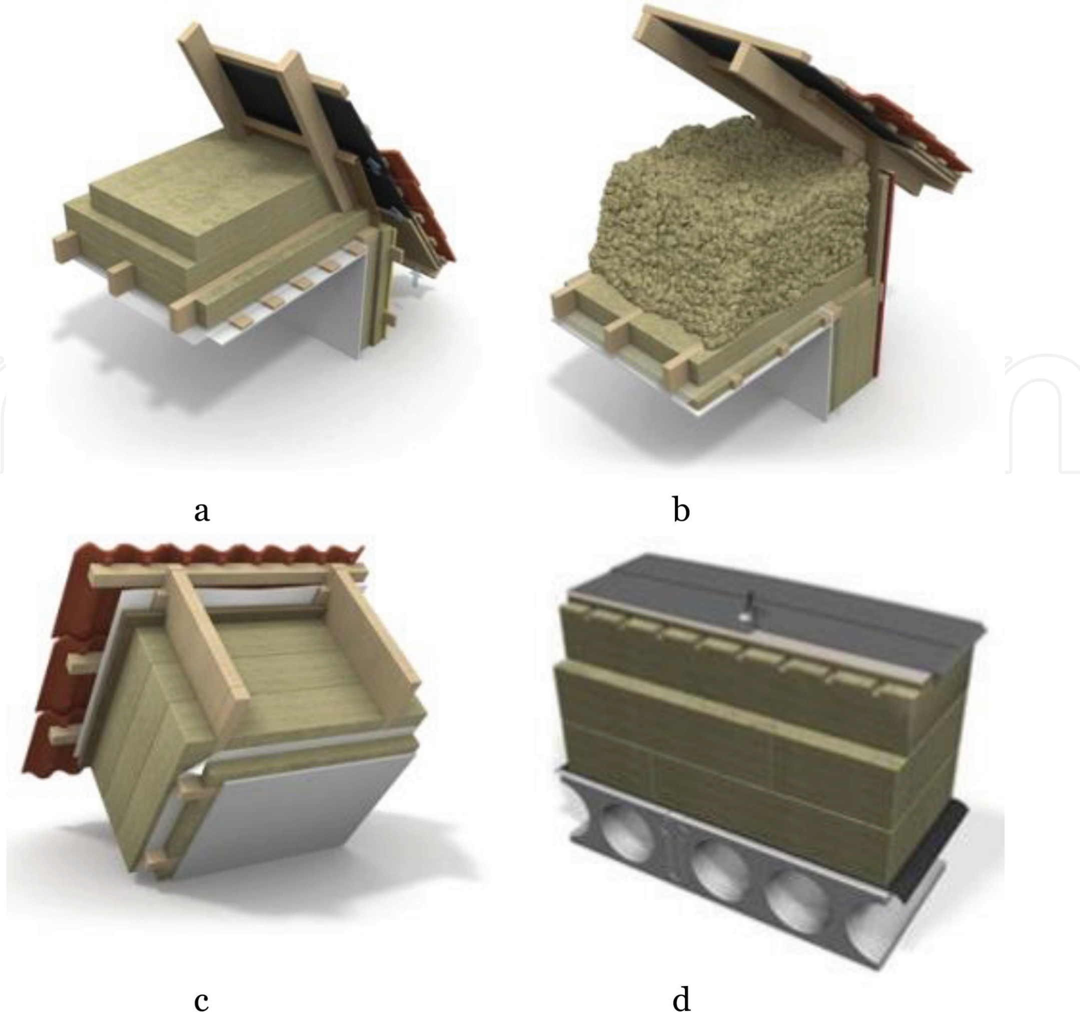

Figure 2.
Structural solutions for roofs: (a and b) thermal insulation of ceiling with an attic, (c) thermal insulation of a pitched roof and (d) thermal insulation of a flat roof.

2.3.2 Thermal insulation of a pitched roof

Rafters with bigger cross-section or glulam beams are used for pitched roof structure of a passive house. An auxiliary frame on the internal side is required to install an auxiliary thermal insulation layer and a tight vapour barrier, which in this system also serves as an air barrier. The vapour barrier is fixed to the bottom of the rafter. With the total thermal insulation layer of 550 mm, the *U* factor value is ≤ 0.07 W/(m^2 K) [12] (**Figure 2c**).

2.3.3 Thermal insulation of a flat roof

The roof of a passive house must be made of at least three layers. We recommend a ventilated PAROC Air structural solution where the insulation part of the intermediate layer has ventilation channels. *U* value is ≤ 0.07 W/(m^2 K) when the thickness of thermal insulation layer is 550 mm (**Figure 2d**).

3. Methods

Design solutions in construction can be evaluated by using different methods. According to the number of criteria, they are divided into single-criteria and multiple-criteria evaluations. In single-criteria evaluation of construction design solutions, construction costs of implementing alternative design solutions are calculated. The most effective alternative is selected according to this criterion [13]. However, construction projects and processes are multifaceted, complex and complicated. For this reason they are analysed by means of multiple-criteria decision-making. Construction projects and processes are multifaceted, complex and complicated.

The following criteria were used in our case:

- Technical: structural reliability of the system, noise level, universality of the building and degree of construction process mechanization
- Legal: environmental issues and occupational safety
- Economic: building site size, construction process duration, expenses and productivity
- Social: forms of labour organizations and motivation level

In this paper two evaluation methods were chosen: cost-benefit analysis and complex proportional assessment (COPRAS) method. Structures of energy efficiency class A house and passive house are compared. The main criteria for the evaluation of building structures are:

- Economic (construction price, length)
- Technological (complexity of technology, quality assurance level)
- Thermal parameters of the structures (thermal resistance, thermal bridges)

3.1 Cost-benefit analysis

In this analysis qualitative characteristics are measured by an expertise method while giving the scores in the grading scale 1–10. Ten is the best score. The criteria are not equally important; therefore the importance of one criterion with respect to another criterion is considered. All calculations and data are presented in a matrix table. The alternative with the highest cost-benefit value *N* is selected. This method enables to compare the analysed alternative in a simple and fast manner [13].

The first step is to select criteria for selected options. Criteria of economic, technological and thermal parameters were selected in order to evaluate different structures. Economic criteria include the cost of material, labour costs, cost of machinery and construction time. Technological criteria include the complexity of construction technology and quality assurance. Thermal parameters of the structures include the thermal resistance of a structure and elimination of thermal bridges.

The second step is to measure the weight (importance) of different criteria. In this paper the best options of technical-economic solutions for a passive house and class A house are analysed; therefore the biggest significance is given to construction price and thermal parameters of the structures.

The third step is to find the utility values of different options and evaluate them by scoring from 1 to 10. Explanation of utility values (from 1 to 10):

Score 10 for the cost of materials, labour costs and cost of machinery means that the amount of money spent to build the structure is the lowest. Other scores show relatively the difference between the prices of the analysed options.

Score 10 for construction time means that the structure was built in the shortest time compared to other analysed options. Other scores show relatively the difference between the construction time of the analysed options. Score 10 for the complexity of construction technology means that the technology of that option is the easiest and the most accessible compared to other options. Quality assurance shows how easy it is (more experience available) to install the structure of the analysed option. Score 10 means that it is easy, and score 1 shows that it is almost impossible.

Score 10 for the elimination of thermal bridges means that thermal bridges are minimized in that option. Other evaluations show relatively how effectively thermal bridges are eliminated in the relevant structure. Thermal resistance factor shows how well heat is protected in that structure option compared to other options. The option with the best thermal resistance factor is scored 10, and other options are scored according to their ability to retain heat.

The fourth step is the calculation of efficiency values taking into consideration the criterion importance. Utility values of different options are multiplied by the criterion importance:

$$b_{ij} = q_i \cdot x_{ij}, i = \overline{1, m};\ i = \overline{1, n} \tag{1}$$

where x_{ij} is the criterion i value for solution j, m is the number of criteria, n is the number of compared options and q_i is criteria significance.

In the fifth step, efficiency values of different criteria for all options are summed up:

$$N_j = \sum_{i=1}^{m} b_{ij}, i = \overline{1, m};\ i = \overline{1, n} \tag{2}$$

where N_j is the efficiency value of the solution option.

The best option is selected in the sixth step. The best variant is found after comparing the efficiency values among the options. The option with the highest efficiency value is the best solution.

3.2 COPRAS method

Goal setting, design and construction processes together with the final construction product and the subsequent operation process form one entity. When separate processes (solutions) of a project improve or deteriorate, the viability of the remaining solutions as well as stakeholders' satisfaction level changes accordingly. Therefore, a precise evaluation and calculation of the effect of all changes on the eventual outcome are important. To this end a complex proportional assessment [13, 14] method is used. Meanwhile, the priority and significance of analysed options directly and proportionately depend on the system of adequately describing criteria, criteria values and significant values. The criteria system is selected, and criteria values as well as initial significance are calculated by experts. Stakeholders (contractor, users, etc.) may modify all this information according to their goals and present circumstances. Therefore, evaluation of the options presents in detail the initial data provided jointly by the experts and stakeholders. The priority and significance of analysed alternatives are calculated in four steps [14, 15]:

1. A normalized decision matrix D is drawn. The goal of this step is to obtain dimensionless (normalized) estimated values from the compared criteria. When normalized estimated values are known, all indicators measured in different units can be compared. The calculation is done by using the formula

$$d_{ij} = \frac{x_{ij} \cdot q_i}{\sum_{j=1}^{n} x_{ij}},\ i = \overline{1, m};\ i = \overline{1, n} \tag{3}$$

where x_{ij} is the criterion i value for solution j, m is the number of criteria, n is the number of compared options and q_i is the criteria importance.

The sum of normalized estimated values $j_i\, d$ of each criterion x_i is always equal to the importance q_i of that criterion:

$$q_i = \sum_{j=1}^{n} d_{ij},\ i = \overline{1, m};\ i = \overline{1, n} \tag{4}$$

The analysed criterion importance value q_i is distributed proportionally to all alternatives a_j with respect to their values x_{ij}.

2. The sums of normalized estimated minimizing (the lower value is better, e.g. price) criteria S_{-j} and maximizing (the higher value is better, e.g. quality) criteria S_{+j} that describe the alternative j are best calculated from the equation

$$S_{+j} = \sum_{i=1}^{m} d_{+ij};\ S_{-j} = \sum_{i=1}^{m} d_{-ij},\ i = \overline{1, m};\ i = \overline{1, n} \tag{5}$$

In this case S_{+j} and S_{-j} values express the level of achieving the goals of the stakeholders of each alternative project. In any case the sums of “pluses” and “minuses” of all alternative projects are always equal to the sums of all maximizing and minimizing criteria values.

3. The relative significance (effectiveness) of compared options is found from their positive (“pluses” of the project) and negative (“minuses” of the project) characteristics. The relative significance Q_j of each variant a_j is found from the formula

$$Q_j = S_{+j} + \frac{S_{-\min} \cdot \sum_{j=1}^{n} S_{-j}}{S_{-j} \sum_{j=1}^{n} \frac{S_{-\min}}{S_{-j}}}, j = \overline{1, n} \tag{6}$$

4. The evaluated options are prioritized. The higher is the Q_j value, the more effective the option is. The method allows to easily evaluate and then select the most feasible solution with a clear physical view of the process. A generalized (reduced) criterion Q_j directly and proportionally depends on the relative influence of the compared criteria values x_{ij} and importance q_i for the final result.

4. Results and discussions

The comparison of different foundation options revealed that strip foundation is the most feasible for houses with basements built on very good soil conditions. Drilled piles are currently the most common foundation type due to economy and fast installation. However, the biggest disadvantage of this foundation for a passive house is the unavoidable thermal bridge at the pole and grade beam joints. Thermal insulation of these spots is almost impossible, and it is a doomed thermal bridge that should be avoided in a passive house.

A monolithic slab is the most appropriate foundation for passive houses due to its closed insulation circuit. Another advantage is suitability for different soil types. Besides, water supply and sewerage systems, power cables, heating system and subfloor, or sometimes even the normal floor, are installed together with the pile foundation. To this end very precise drawings of the house are required with all engineering and utility systems planned in advance. No significant changes of the house design are possible at later stages of construction. This disadvantage is eliminated by good planning and deliberations about the future use of the house. A monolithic slab becomes the most economic variant after the price of ground floor installation is added to the strip or pile foundations. It is 76% cheaper than pile foundation with ground floor installation and twice cheaper than strip foundation with ground floor installation.

4.1 Comparison of the efficiency among foundation options

The analysed options of a passive house foundation structures are as follows: F1P, strip foundation together with the first storey floor; F2P, pile foundation together with the first storey floor; and F3P, concrete slab floor.

The analysed options of energy efficiency class A house foundation structures are as follows: F1, strip foundation with first storey floor; F2, pile foundation with first storey floor; and F3, concrete slab floor. The obtained results are presented in **Figure 3**.

The comparison of utility values among the foundation options showed that concrete slab floor received the highest scores both in a passive house and in

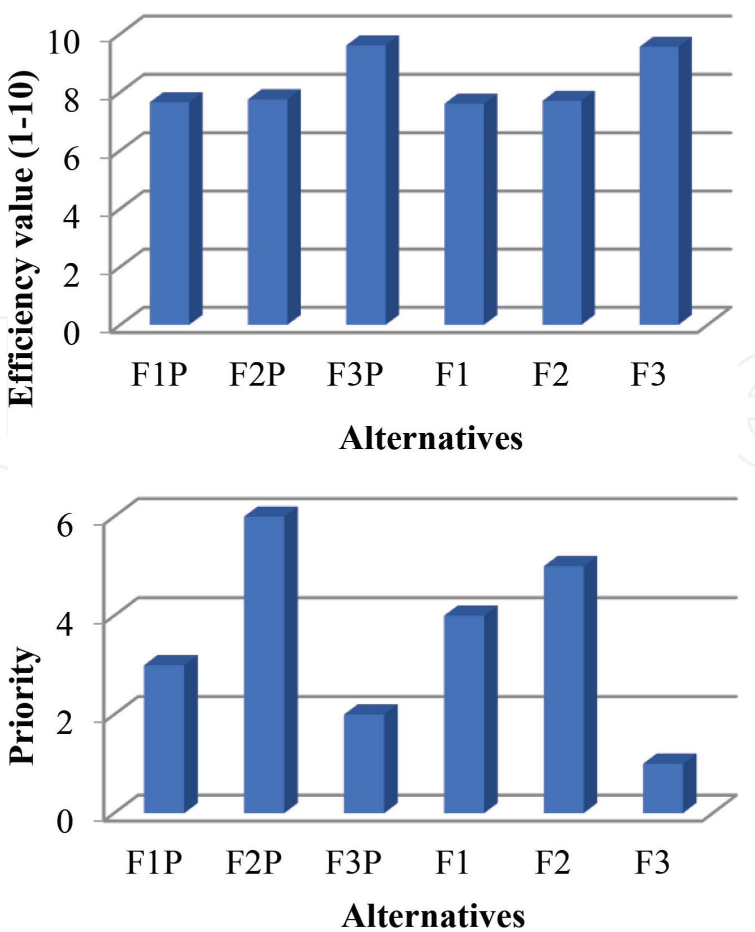

Figure 3.
Comparison of the efficiency among foundation options.

efficiency class A house. Efficiency values of concrete slab floor options were much higher than strip or pile foundations. The reason is much higher thermal parameters of the concrete slab floor than strip or pile foundation. The floor is installed together with the foundation slab and thus reduces the total price of the house. The analysis has shown that the best foundation option for energy-efficient houses is a concrete slab floor.

4.2 Comparison of the efficiency among wall options

The analysed options of a passive house wall structures are as follows: W1P, timber stud wall with sheet cladding; W2P, glued laminated timber I-joist stud wall with brick finishing; and W3P, plastered silicate block wall.

The analysed options of efficiency class A house foundation structures are as follows: W1, timber stud wall with sheet cladding; W2, glued laminated timber I-joist stud wall with brick finishing; and W3, plastered silicate block wall. The obtained results are presented in **Figure 4**.

The comparison of economic indicators for various options of passive house walls showed that timber stud walls are the best option. The cost of materials makes the major part in the price of plastered brick structures. Thermal insulation of such walls requires a thicker insulation layer in order to reach the passive house criteria for the walls. To improve the energy efficiency of such walls, the brickwork materials with better heat transfer factors should be chosen in order to have a thinner insulation layer. Timber stud walls require more labour, but 420 mm of the total thermal insulation layer is sufficient. The thermal insulation layer is installed between the load-bearing elements of the framework and auxiliary studs. The

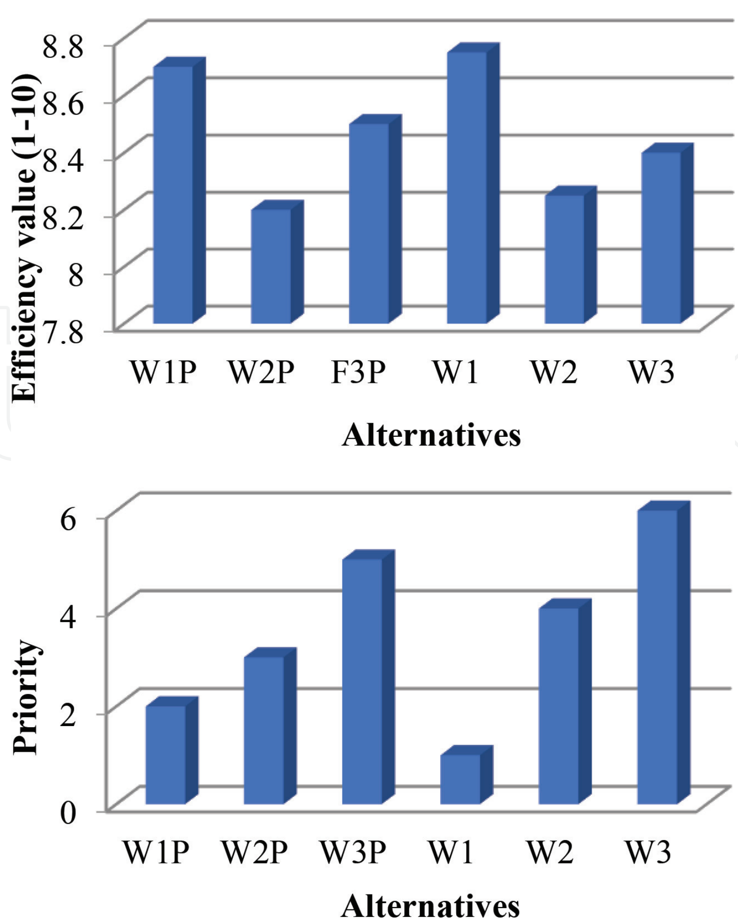

Figure 4.
Comparison of the efficiency among wall options.

load-bearing elements can be I-beams, box cross-sectional beams or glulam box beams. It should be noted that supervision of labour quality is vital for the building of such walls. Thermal insulation materials are installed in several layers. The tightness of air and vapour barrier must be ensured. According to the obtained data, the biggest price difference of alternative options is caused by the selected façade finishing. The brick finishing façade on stud walls increases the price of such walls significantly compared to sheet cladding finish. The sharp rise in plastered brick wall price is caused by the selected finishing plaster on the exterior. Timber stud walls with sheet cladding are 45% more efficient than silicate block walls and 51% more efficient than glulam I-joist stud walls with brick finishing.

4.3 Comparison of the efficiency among roof options

The analysed options of a passive house wall structures are as follows: R1P, insulation of a pitched roof ceiling with a cold attic; R2P, insulation of a pitched roof; and R3P, insulation of a flat roof concrete slab.

The analysed options of efficiency class A house foundation structures are as follows: R1, insulation of a pitched roof ceiling with a cold attic; R2, insulation of a pitched roof; and R3, insulation of a flat roof concrete slab. The obtained results are presented in **Figure 5**.

The comparison of flat and pitched roofs of the passive house with a cold and thermally insulated roof showed that a timber frame roof with thermally insulated ceiling and a cold attic is the best option for a single-family house. The labour cost indicator for a flat roof is economically the best compared to other alternatives;

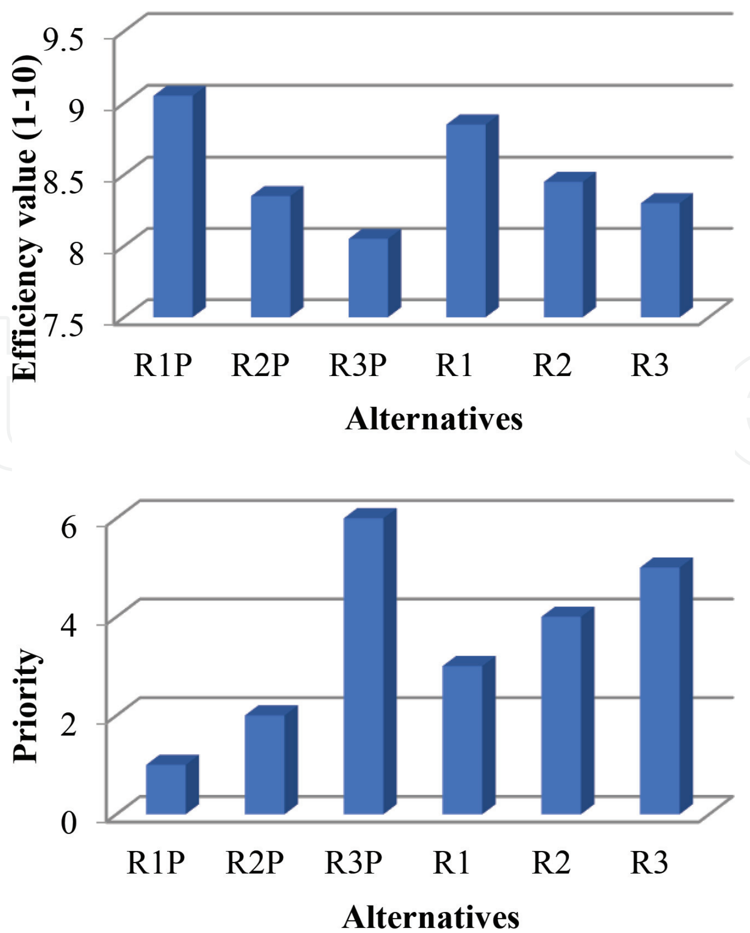

Figure 5.
Comparison of the efficiency among roof options.

however the price of the supporting structure and roof coat can be several times higher than in other options. Therefore, the total price of such a roof increases significantly. Insulation of the entire pitched roof requires much more insulation materials, and the height of the main rafters must be increased. Therefore, the total labour costs of such a roof increase significantly. The best economic effect is achieved by leaving the pitched roof uninsulated and installing the thermal insulation layer on the ceiling. The article analyses two different insulation options: using only insulation sheets and combining insulation sheets with bulky insulation material. Although the price of bulky insulation materials is lower, special blowing equipment is required. The combined insulation layer is also thicker. Attic insulation by means of rock wool sheets only is by 2% more economic than insulation with bulky foam and 25% cheaper than installing thermal insulation between rafters. A flat roof with concrete slab ceiling is several times more expensive than other options; therefore it is not recommended.

5. Conclusions

According to the passive house standard, an energy-efficient house is a building where energy is saved by architectural, structural and technological solutions. To meet the passive house standard requirements, the house must be tight, use renewable energy and employ various energy-saving methods and the planning done with respect to orientation.

The technical-economic comparison of the main structures of a passive house revealed that it is cheaper to install an adequately designed concrete slab foundation than to build strip or pile foundation and the floor separately.

Timber stud walls are the cheapest wall option for a passive house and 45–51% cheaper than other options. The comparison of roofs and ceilings showed that insulation of the ceiling is 25% more efficient than insulation of the roof.

The comparison of the main envelope element efficiency by multiple-criteria evaluation methods showed that it is economically feasible to install concrete slab on ground foundation, stud walls with sheet cladding and a pitched roof with insulated ceiling.

Conflict of interest

The author declares no conflict of interest.

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