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STRUCTURAL AND TECHNOLOGICAL INVESTIGATIONS OF BUILDING ENVELOPE

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The article examines technological and structural solutions for walls, roofs, floors in order to find the most effective barriers for each material and its thickness. Thermal insulation materials are the key factor to be considered in energy efficient buildings. Selected alternative materials are mineral wool, polystyrene and polyurethane foam. Thermal parameters, economic and technological indicators are compared within the envelope. The optimal thickness of the envelope component is found by calculating every envelope option by means of test utility method. The most efficient insulation material is determined by the simple additive weighting (SAW) method. The optimal thickness of insulation materials: 400 mm for the roof, 300 mm for walls and 300 mm for floors. The most effective materials are as follows: polyurethane foam for the roof, polyurethane foam for walls and polystyrene for floors.

Keywords: Envelope components, Technological solutions, Multiple criteria evaluation.

1 INTRODUCTION

Efficient energy use is important in modern buildings because of high energy costs and CO_2 emissions. These reasons have led to the development of energy efficient buildings. The key factors in energy efficient building are insulation of partitions, their tightness and absence of thermal bridges (Buxbaum *et al.* 2007). A modern building must be economical and use energy resources efficiently by means of modern technologies. Energy efficient buildings have numerous environmental, economic, and social advantages versus traditional buildings. At the same time, there are a lot of options in the choice of insulation materials, insulation layer thickness, glazing and other structural elements of the building.

The article compares the alternative options for wall, roof and floor structures. Rock wool, polystyrene foam and spray-applied polyurethane foam can be alternatively used for thermal insulation. Thermal insulation materials are the key factor to be considered in energy efficient buildings. The present paper compares envelope insulation materials for façades in modern buildings.

2 APPLIED METHODOLOGY AND METHODS

2.1 Structural Solutions for Envelopes

The paper analyses the thermal insulation solutions for a flat roof constructed on reinforced concrete slab (Figure 1). The aim is to find the most efficient insulation material and the insulation layer thickness. The following alternatives were selected for the analysis: rock wool, polystyrene foam sheets and spray-applied polyurethane foam.

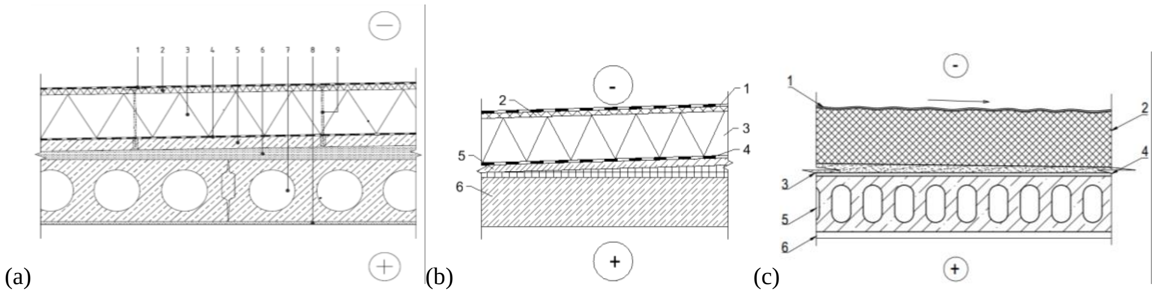

Figure 1. Structural solutions for flat roofs: (a) rock wool; (b) polystyrene foam sheets; (c) spray-applied polyurethane foam: 1 - Waterproofing roof coating; 2 - PAROC ROB 60, d=20 mm; 3 - PAROC ROS 30; 4 - Vapour and moisture control layer PAROC WMV 020 bas; 5 - Levelling layer, d>50 mm; 6 - Fall creating layer; 7 - Reinforced concrete slab; 8 - Finishing layer – plaster, d<10mm; 9 - Fixture (paroc.lt); (b) 1 - Waterproofing roof coating; 2 - Top layer from laminated polystyrene sheets; 3 - Bottom layer from laminated polystyrene sheets; 4 - Vapour and moisture control; 5 - Fall forming and levelling layer; 6 - Reinforced concrete slab (kaunosilas.lt); (c) 1 - UV membrane; 2 - Polyurethane foam POLIURETAN SPRAY S-403E-W; 3 - Pitch forming layer; 4 – Interlayer; 5 - Reinforced concrete slab; 6 - Finishing layer (izoputos.lt).

Thermal insulation of flat roofs poses high requirements for insulating material because the roof surface must have resistance to various impacts such as extreme temperatures, snow, rain and wind loads. The foam sprayed on the roof hardens after several minutes and becomes resilient to foot traffic. Now it has to be covered with UV control layer.

Brick wall insulation alternatives are also analysed in order to find the most effective material and insulation layer thickness. The following insulation alternatives were selected: rock wool, polystyrene foam sheets and spray-applied polyurethane foam (Figure 2).

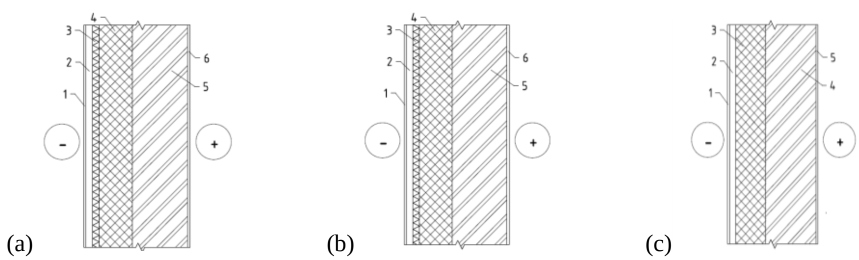

Figure 2. Structural solutions for walls: (a) rock wool; (b) polystyrene foam sheets; (c) spray-applied polyurethane foam: (a) 1 - External finishing layer; 2 - Ventilated air gap, 30 mm; 3 - Wind barrier; 4 - Thermal insulation with PAROC FAS B; 5 - Brick wall; 6 - Finishing layer (izoputos.lt); (b) 1 - External finishing layer; 2 - Ventilated air gap, 30 mm; 3 - Wind barrier; 4 - Thermal insulation with EPS 70; 5 - Brick wall; 6 - Internal finishing layer (paroc.lt, kaunosilas.lt); (c) 1 - External finishing layer; 2 - Ventilated air gap, 30 mm; 3 - Polyurethane foam POLIURETAN SPRAY S-303E-W; 4 - Brick wall; 5 - Internal finishing layer (izoputos.lt).).

A framework made of vertical or horizontal wooden beams or metal profiles must be built for the thermal insulation of walls. The framework ensures the even thickness of insulation material and smooth surface. Polyurethane foam is sprayed into the carcass spaces and after several minutes of hardening the excessive protruding surfaces can be cut and the finishing layer of the wall can be installed.

Similarly, floor on the ground installation solutions are analysed by using rock wool and polystyrene foam in order to find the most effective insulation layer thickness (Figure 3).

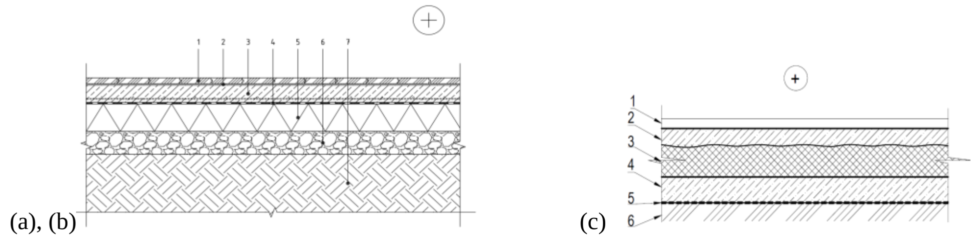

Figure 3. Structural solutions for floor: (a) rock wool; (b) polystyrene foam sheets; (c) spray-applied polyurethane foam: 1 - Floor coating, d=8-14 mm; 2 - Glue layer, d=2-5 mm; 3 - Reinforced levelling layer, d>50 mm; 4 - Separation layer – PE membrane; 5 - PAROC ROS 20; 6 - Drainage layer, d>80 mm; 7 - Compacted soil (paroc.lt); (b) 1 - Floor coating, d=8-14 mm; 2 - Glue layer, d=2-5 mm; 3 - Reinforced levelling layer, d>50 mm; 4 - Separation layer – PE membrane; 5 - Polystyrene foam EPS 150; 6 - Drainage layer, d>80 mm; 7 - Compacted soil (paroc.lt); (c) 1 - Floor coating; 2 - Levelling concrete layer; 3 – Polyurethane foam POLIURETAN SPRAY S-403E-W; 4 - Concrete floor slab; 5 - Waterproofing membrane; 6 - Compacted soil (izoputos.lt).

For the insulation of floor on the ground the soil under the floor must be compacted and the waterproofing layer must be installed. The main difference between using polystyrene foam sheets and rock wool for thermal insulation of floors is that the sub-base concrete layer is required. Polyurethane foam is sprayed onto the hardened concrete layer. A levelling reinforced concrete layer is installed on top of hardened polyurethane foam. The floor coating is installed on top of the hardened concrete layer.

Polyurethane foam with closed pores must be used on flat roofs to ensure water tightness and resistance to heavy loads (high compressive strength). Polyurethane foam with open pores is more suitable for walls protected from the elements. Polyurethane foam with closed pores must be used for floors and ceilings due to high compressive strength requirements.

2.2 Thermal Parameters of Envelope Components

The heat transfer coefficient of the roof was calculated for a renovated building. Rock wool sheets, polystyrene foam sheets and spray-applied polyurethane foam can be alternatively used for thermal insulation. The λ_D values of rock wool and polystyrene foam are similar, therefore the declared heat transfer coefficient values for both material are 0,037 W/(m·K).

The thickness of thermal insulation layer for wall in increased by 100 mm from 200 mm to 500 mm.

2.3 Comparison of Building Envelope Components in Terms of Economy and Labour Costs

Calculations for the comparison of economy were done by using the computing software SISTELA. The roof installation prices are given in EUR/m^2. Installation costs of the following levels are calculated: two layers of membrane roofing, thermal insulation layer (standard and load bearing), vapour barrier, fall forming layer and levelling layer.

2.4 Finding the Optimal Thickness of Envelope Element

Construction projects and processes are multifaceted, complex and complicated. For this reason, they are analysed by means of multiple-criteria decision-making.

The following algorithm was used in multiple-criteria decision-making regarding the alternative solutions:

Evaluation criteria system is designed → The weighting factors (significance) are assigned to the criteria, % → Criteria values are set → The efficiency value in zero to ten point system is set → The efficiency value is calculated → The total efficiency value of alternative solutions is calculated.

After making the multiple-criteria evaluation, summing up the scores and comparing them, we may find the optimal option (Miniotaite 2016, Janusaitis 1998).

2.5 Calculation of the Most Rational Envelope Component Material

SAW (Simple Additive Weighting) method was used to find the most effective structure of the wall.

Eq. (1) describes the Multiple-criteria decision-making method SAW:

$$S_j = \sum_{i=1}^{m} \omega_i \cdot \tilde{r}_{ij} \tag{1}$$

where: S_j multiple-criteria evaluation value of the j^{th} option; ω_i is weight of the i^{th} indicator; $\tilde{r}_{ij}$ - normalized value of the i^{th} indicator for the j^{th} option.

To find the multiple-criteria evaluation value normalized values of criteria have to be obtained. The normalization procedure depends on multiple-criteria decision-making method. The normalized value of a criterion is calculated from the following equations.

(1) For the maximization of matrix criterion (Eq. (2)):

$$\tilde{r}_{ij} = \frac{\min_j r_{ij}}{r_{ij}} \tag{2}$$

where r_{ij} is the value of the i^{th} criterion of the j^{th} option; $min\ _j r_{ij}$ is the lowest value of the i^{th} criterion of the j^{th} option.

(2) For the minimization of matrix criterion (Eq. (3)):

$$\tilde{r}_{ij} = \frac{r_{ij}}{\max_j r_{ij}} \tag{3}$$

where $max\ r_{ij}$ - the highest value of the i^{th}–criterion of the j^{th} option (Ginevicius *et al.* 2008).

3 RESULTS

The most effective roof thickness of 400 mm was selected after making the multiple-criteria decision and calculating the efficiency value with respect to thermal parameters, cost of materials, labour costs and machinery costs. The same result was achieved in all cases: using rock wool, polystyrene foam and spray-applied polyurethane foam. The results are presented in Figure 4a (alternatives: 180 mm; 200 mm; 300 mm; 400 mm; 500 mm thick layer of rock wool).

The most effective wall thickness of 300 mm was selected after making the multiple-criteria decision and calculating the efficiency value with respect to thermal parameters, cost of materials, labour costs and machinery costs. The same result was achieved in all cases: using rock wool, polystyrene foam and spray-applied polyurethane foam. The results are presented in Figure 4b (alternatives: 180 mm; 200 mm; 300 mm; 400 mm; 500 mm thick layer of polystyrene foam).

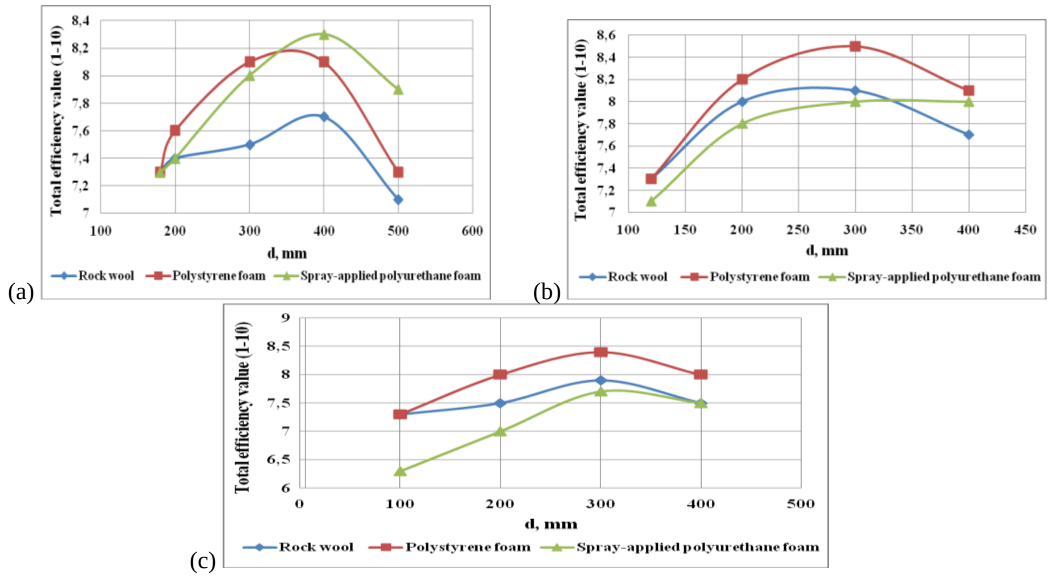

Figure 4. Relationship between the efficiency value and envelope component thermal insulation layer: (a) roof; (b) wall; (c) floor.

The most effective floor thickness of 300 mm was selected after making the multiple-criteria decision and calculating the efficiency value with respect to thermal parameters, cost of materials, labour costs and machinery costs. The same result was achieved in all cases: using rock wool, polystyrene foam and spray-applied polyurethane foam. The results are presented in Figure 4c (alternatives: 180 mm; 200 mm; 300 mm; 400 mm; 500 mm thick layer of spray-applied polyurethane foam). Options: E1ST – the optimal layer thickness in the case of rock wool; E2ST – the optimal layer thickness in the case of polystyrene foam; E3ST – the optimal layer thickness in the case of spray applied polyurethane foam.

The following values of options were obtained from the calculations under SAW method and summing up the values of options with estimated weights of their criteria: E1R = 0,727, E2R = 0,841 and E3R = 0,847 (Table 1).

Table 1. Normalized matrix of solutions (roof).

Criteria	**Weights of criteria**	**Criterion unit of measure**	**Alternatives**			**The values of options with estimated weights of their criteria**		
			E1R	**E2R**	**E3R**	**E1R**	**E2R**	**E3R**
Complexity of construction technology	0,09	in points	0,9	1	1	0,081	0,09	0,09
Quality assurance	0,1	in points	0,9	1	0,9	0,09	0,1	0,09
Tightness of envelope component	0,1	in points	0,8	0,9	1	0,08	0,09	0,10
Durability	0,1	in years	0,8	1	0,8	0,08	0,1	0,08

Table 1 (continued). Normalized matrix of solutions (roof).

Criteria	**Weights of criteria**	**Criterion unit of measure**	**Alternatives**			**The values of options with estimated weights of their criteria**		
			E1R	**E2R**	**E3R**	**E1R**	**E2R**	**E3R**
Thermal parameters	0,15	W/(m^{2}K)	0,822	0,822	1	0,1233	0,1233	0,15
Costs of materials	0,15	EUR/m^2	0,52	0,786	1	0,078	0,118	0,15
Labour costs, Eur/m^2	0,12	man-hour/m^2	0,84	1	0,924	0,101	0,012	0,1109
Machinery costs	0,1	machine-hours/m^2	0,94	1	0,76	0,094	0,1	0,076
AMOUNT						0,727	0,841	0,847

The most rational option is E3R (400 mm thick layer of polyurethane foam). The highest evaluation criteria value under the SAW method corresponds to the most rational option. Results are presented in Figure 5.

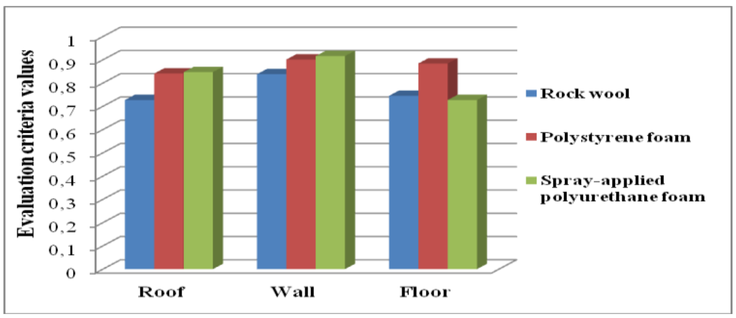

Figure 5. Evaluation criteria values: roof; wall; floor.

4 CONCLUSIONS

Spray-applied polyurethane foam is an effective insulation material due to high work efficiency, good thermal insulation properties and price.

Building modernization calculations done by efficiency value method showed that the optimal thickness of thermal insulation layer for the roof is 400 mm, for the wall is 300 mm and for the floor is 300 mm.

The multiple-criteria evaluation of the building modernization by SAW method showed that the most rational insulation material for the roof is spray-applied polyurethane foam, which is also the best option – for wall insulation, and polystyrene foam for – floor insulation.

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