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The selecting of building insulation material by the analytic hierarchy process

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Abstract. Today one of the Federal programs implemented in Russia at the state level, is a program of energy conservation and energy efficiency to reduce the specific consumption of fuel and energy resources. In developed countries, private landlords are using almost 30% of all generated power, i.e. almost as much as industry and more than all transport combined. About 80% of the energy consumed goes to space heating, but much of it is often wasted due to a mismatch of home insulation with the adopted standards. Thus, a rational choice of insulating material is one of the most important tasks to reduce heat losses in residential buildings. There is a wide variety of building insulation materials available for purchase. For heat insulation of external walls of residential buildings are most often used single-piece insulation materials – batts, blankets, panels. Their essential advantage in comparison with loose-fill materials, such as crushed expanded polystyrene, expanded vermiculite, claydite, are the simplicity and speed of installation, acceleration of construction works and improvement of their quality. Autoclaved aerated concrete blocks are used traditional for thermal walls insulation, they does not rot, does not burn, does not emit toxic substances during operation, has an average water vapor permeability and, therefore, well regulates the humidity in the room. However, the masonry of aerated concrete blocks has a significant disadvantage – a large average density. Alternatively, the modern industry offers a wide range of synthetic insulating materials, the most popular are fiberglass, mineral (rock or slag) wool, plastic or natural fibers, polystyrene, polyisocyanurate, polyurethane foam boards. As well become increasingly popular natural materials such as cellulose, peat blocks, cork, fiberboard, insulation from flax or hemp fibers. All of these materials have their advantages and disadvantages, so the task of choosing the optimal variant is complex and requires special methods to eliminate the subjectivity of evaluation. The article describes the approach to selecting the best option of building insulation material from the available options by the set of its quantitative and qualitative characteristics. It is proposed to carry out the evaluation of options and selection of the best option based on the analytic hierarchy process. The article presents the results of the selection of the most appropriate thermal insulation material for residential buildings.

1. Introduction

On 23 November 2009 in Russian Federation was adopted the Federal law on energy conservation and energy efficiency (261-FZ), which aims to reduce the intensity of electricity, heat, water and gas consumption in order to help Russia approach European consumption levels by 2020. In the framework of the law stipulates energy intensity of industrial production by 40%. Major objectives include significantly reduce specific energy losses and the energy intensity of produced goods that will allow to increase the competitiveness of the Russian economy [1].

Private landlords are using almost 30% of all generated power, i.e. almost as much as industry and more than all transport combined, therefore, the problem of energy saving in residential buildings is very important [2].

In the average home for 50% to 70% of the energy used for heating and cooling, but much of it is often wasted due to a mismatch of home insulation with the adopted standards. In many homes insulation is the most practical and cost-effective way to make a house more energy efficient, keeping it cooler in summer and warmer in winter and saving up to 80% in heating and cooling losses, which is especially important because the average residential electricity and natural gas prices are expected to rise by 5-10% per year. Thus, a rational choice of thermal insulating material, which acts as a barrier to heat loss and heat gain, is one of the most important tasks to reduce heat losses in residential buildings [3-5].

There is a wide variety of natural or synthetic thermal insulation materials, which can be attributed to two types - bulk insulation, which acts as a barrier to heat flow between home and the outside, and reflective insulation, which is generally used to keep home cool in summer by deflecting radiant heat. Reflective insulation is best suited in hot and very sunny climates and bulk insulation - in cooler climates. Some insulation products combine features of both bulk and reflective insulation.

The basic requirements to the thermal insulation materials are [6-8]:

1. Low thermal conductivity – the lower coefficient of thermal conductance (or the higher of thermal resistance (R-value, the reciprocal of thermal conductivity), the more heat is held indoors and the smaller thickness of the insulating material is required.
2. Low average density - the lightweight insulation materials can reduce the weight of buildings and structures, and as a consequence decreasing of transport charges in the construction process.
3. High gas and vapour permeability – low permeability leads to the accumulation of moisture in the contact area of insulating material with the building designs, the moisture activates the corrosion process until the destruction of the structure.
4. Low water absorption - thermal conductivity of insulation materials sharply increases during the humidification of material.
5. The choice of finish – the availability of choice of different variants of decorative finishes directly on the insulation without additional foundations.
6. Durability.
7. Environmentally friendly.
8. Fire safety - an advantage have a non-combustible or slow-burning materials.
9. Chemical and biological resistance, heat resistance.
10. Low cost - the costs of insulation can amount to a significant proportion of the costs involved in construction.
11. High sound absorption and sound proofing.
12. Durability.

Autoclaved aerated concrete (AAC) blocks are used traditional for thermal walls insulation, they are composed of all natural raw materials and, therefore, are recyclable. They does not rot, does not burn, does not emit toxic substances during operation. AAC blocks are excellent soundproofing material, they have an average water vapor permeability and, therefore, well regulate the humidity in the room. AAC blocks can be cut with a saw blade and can be drilled easily. However, the masonry of AAC blocks has some significant disadvantages – a large average density, low R-value (relative to BuildingGreen-recommended R-values) and impossibility to use it as a finish (it is more porous and needs cladding or stucco on the outside that will not allow it to absorb moisture) [9].

Alternatively, the modern industry offers a wide range of synthetic thermal insulating materials. The most common insulation used in modern times is fiberglass, which is commonly used in two different types - blanket (batts and rolls) and loose-fill. Fiberglass is non-combustible insulation material with low R-value, high gas and vapour permeability. The main disadvantage of fiberglass is the danger to the eyes, lungs, and even skin if the proper safety equipment is not worn [10].

Another popular thermal insulating material is mineral (rock (consists of fibers of natural stone (basalt or diabase) or slag (consists of fibers made from iron-ore waste)) wool, which is commercially available in a wide variety of forms, shapes, and sizes, including board, batt, loose-fill, spray-applied, and pipe insulation for many common and specialized applications. The main advantages of this type of insulation material are high resistance to fire (it does not burn until temperatures reach beyond 1000°C), high R-value, naturally moisture-resistace, mold, fungi, and bacteria resistance, excellent sound absorption properties. But as well as fiberglass mineral wool can be hazardous to health if protective gear does not worn when installing insulation - the tiny fibers can be inhaled and cause respiratory disease [11].

Also while not the most abundant of thermal insulating materials are polyurethane, polystyrene, polyisocyanurate foams. They are dimensionally stable, moisture, mold, fungi, and bacteria resistant, durable and have an excellent R-values and small average density. Foams are available in a wide variety of forms (rigid board, molded foam, spray, pour-in-place foam) that provides them versatility. The main disadvantage of foams is flammability [12].

As well become increasingly popular natural materials such as cellulose, peat blocks, cork, fiberboard, insulation from flax or hemp fibers. Natural materials are eco-friendly, have satisfactory R-values, low toxicity levels, high gas and vapour permeability, but they are more expensive than their more commonly used counterparts, such as fiberglass, polystyrene and rock wool [13].

2. Experimental section

Table 1 presents the most popular in Russia thermal insulating materials for residential buildings and their characteristics [9-13].

Table 1. Thermal insulating materials for residential buildings

Thermal insulating materials	Fire safety class	Average density, kg/m^3	Thermal conductivity, W/(m*°C)	Cost, RUB/m^3	Lifespan / warranty, years	Vapour permeability coefficient, mg/(m*h*Pa)	Water absorption by volume, no more than %
TECHNOVENT STANDARD	KM0	80	0.038	2917	50	0.3	1.5
XPS TECHNONICOL CARBON ECO	KM5	29	0.029	4953	50	0.011	0.2
LOGICPIR WALL	KM4	35	0.022	10 400	25	0.038	1
URSA GEO Universal plate	KM0	15	0.036	1471	50	0.51	1
AKOTERM FLAX	KM4	30	0.037	4800	75	0.4	1
AEROC EcoTerm Plus (D300)	KM0	300	0.088	2400	50	0.25	20

Thermal insulating slabs TECHNOVENT STANDARD are produced by TechnoNICOL Company, the largest manufacturer and supplier in Russia and Europe which offers a wide range of roofing, water-, sound-, and heat insulating materials. This material is nonflammable, waterproofing, heat and sound insulating material, made of basalt rock stonewool with a low-phenol binder.

Thermal insulating panels XPS TECHNONICOL CARBON ECO (produced by TechnoNICOL Company) are made of extruded polystyrene foam saturated with nanoscale carbon particles, which reduces the thermal conductivity of the material and increases its strength.

Thermal insulating plates LOGICPIR WALL (produced by TechnoNICOL Company) are made on the basis of rigid polyisocyanurate with both sides laminated of foil.

Thermal insulating material URSA GEO Universal plate (produced by URSA, one of the leading companies in the construction market of Europe) is mineral warm and sound insulation on the basis of fiber glass.

Thermal insulating plates AKOTERM FLAX (produced by the Belarusian company AKOTERM) are made of a flax fiber (85%) and an adhesive component (15%), which is evenly distributed over all cover of a plate.

AEROC EcoTerm Plus (D300) (produced by the company «AEROC Saint Petersburg») – the AAC blocks with average density 300 kg/m^3.

All of these materials have their advantages and disadvantages, so the task of choosing the optimal option is complex and requires special methods to eliminate the subjectivity of evaluation. One of such methods is the analytic hierarchy process, which allows to solve the problem of choice on set of qualitative and quantitative characteristics [14-17].

The decision problem is decomposed into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The method is based on constructing a hierarchy starting from the top (goal), through intermediate levels (a group of factors or criteria that relate the alternatives to the goal) to the very bottom level (the list of alternatives for reaching the goal). Each element of the system, except for the top one, is subordinate to one or more other elements. The criteria can be further broken down into subcriteria, sub-subcriteria, and so on, in as many levels as the problem requires.

Then the hierarchy is analyzed through a series of pairwise comparisons: the criteria are pairwise compared against the goal for importance, the alternatives are pairwise compared against each of the criteria for preference. The comparisons are processed mathematically: at each level the set of matrix of pairwise comparisons is built (table 2) [18].

Table 2. Matrix of pairwise comparisons

	A_1	A_2	A_3	…	A_n
A_1	w_1/w_1	w_1/w_2	w_1/w_3	…	w_1/w_n
A_2	w_2/w_1	w_2/w_2	w_2/w_3	…	w_2/w_n
A_3	w_3/w_1	w_3/w_2	w_3/w_3	…	w_3/w_n
…	…	…	…	…	…
A_n	w_n/w_1	w_n/w_2	w_n/w_3	…	w_n/w_n

A_1, A_2, …, A_n is the set of n elements and w_1, w_2,…, w_n respectively, their weight, or intensity. Weight, or intensity, of each element is compared with the weight or intensity of any other element of the set in relation to the common property or the goal (i.e. w_1/w_1 means comparison, not dividing the weights of these elements).

The comparison of weights can be represented as follows: the elements of any level are compared with each other regarding their effects on guided element on 9-point scale (from 1 – equal importance to 9 – very strong superiority).

If the element A_1 is dominant over the element A_2, the cell corresponding to the row A_1 and column A_2 is filled with an integer, and the cell corresponding to the row A_2 and column A_1 is filled with the integer reciprocal (fraction).

Then at each level the synthesis of priorities is made, i.e. for each row the geometric mean is calculated. The vector of priorities is obtained by dividing each geometric mean by the sum of all geometric means (table 3) [19].

Table 3. Calculating of the vector of priorities

	A_1	…	A_n	The rating of the eigenvector components by row	Vector of priorities
A_1	w_1/w_1	…	w_1/w_n	$\sqrt[n]{\frac{w_1}{w_1}\times\ldots\times\frac{w_1}{w_n}} = a_1$	$\frac{a_1}{\sum_{i=1}^{n} a_i} = x_1$
…	…	…	…	…	…
A_n	w_n/w_1	…	w_n/w_n	$\sqrt[n]{\frac{w_n}{w_1}\times\ldots\times\frac{w_n}{w_n}} = a_n$	$\frac{a_n}{\sum_{i=1}^{n} a_i} = x_n$

Multiplication of the matrix by the vector of priorities is as follows:

$$\begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \ldots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \ldots & \frac{w_2}{w_n} \\ \ldots & \ldots & \ldots & \ldots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \ldots & \frac{w_n}{w_n} \end{pmatrix} * \begin{pmatrix} x_1 \\ x_2 \\ \ldots \\ x_n \end{pmatrix} = \begin{matrix} \frac{w_1}{w_1}x_1 + \frac{w_1}{w_2}x_2 \ldots + \frac{w_1}{w_n}x_n = Y_1 \\ \frac{w_2}{w_1}x_1 + \frac{w_2}{w_2}x_2 \ldots + \frac{w_2}{w_n}x_n = Y_2 \\ \ldots \\ \frac{w_n}{w_1}x_1 + \frac{w_n}{w_2}x_2 + \ldots + \frac{w_n}{w_n}x_n = Y_n \end{matrix} \tag{1}$$

It is important to note that in the matrix of pairwise comparisons there is no ratio w_i/w_j, there are only integers or integer reciprocals from a scale. This matrix in the general case is inconsistent. Algebraically the problem of consistency is the solution of the equation $Aw=nw$, $A=(w_i/w_j)$, and the total task is the solution of the equation $A'w'=\lambda_{max}\cdot w'$, $A'=(a_{ij})$, where λ_{max} is the largest eigenvalue of the matrix of pairwise comparisons A.

To check the consistency of each matrix the eigenvalues of the matrix are calculated (as the sum of the vector components obtained by multiplying the matrix of pairwise comparisons by the vector of priorities):

$$\lambda_{max}=\sum_{i=1}^{n} Y_i \tag{2}$$

Next, the index of consistency (IC) and consistency ratio (CR) are calculated:

$$IC = (\lambda_{max} - n)/(n - 1), \tag{3}$$

where λ_{max} – eigenvalue of the matrix, n – the number of compared elements.

$$CR=IC/RI, \tag{4}$$

where RI – random index.

CR and IC should not exceed 10%. Otherwise, the quality of the judgments should be improved, perhaps by revising the way in which questions are asked when conducting pairwise comparisons.

When conducting assessments it is important to keep in mind all compare items to comparison was relevant. To conduct a reasonable numerical comparisons should not compare more than 7±2 elements.

Then hierarchical synthesis is conducted, i.e. the sum of all the weighted components of the corresponding eigenvectors of the hierarchy level lying before is calculated [20].

3. Results section

The described method was used for selecting of the most appropriate thermal insulation material for residential buildings.

The criteria pairwise comparisons, the vector of priorities and the result of their multiplication Y_i are presented in table 4.

Criteria:

C_1 - thermal conductivity; W/(m*°C);
C_2 - fire safety class;
C_3 - vapour permeability coefficient, mg/(m*h*Pa);
C_4 - cost, RUB/m^3;
C_5 - average density, kg/m^3;
C_6 -lifespan / warranty, years;
C_7 - water absorption by volume, no more than %

The eigenvalue of the matrix, IC and CR were calculated by the equations (2), (3) and (4), CR and IC are not exceed 10%.

Table 4. Calculating of the criterion vector of priorities

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	The rating of the eigenvector components by row	Criterion vector of priorities	Y_i
C_1	1	1	2	3	4	8	9	2.402	0.294	1.951
C_2	1	1	2	3	4	8	9	2.402	0.294	1.951
C_3	1/2	1/2	1	2	3	7	8	1.480	0.181	1.244
C_4	1/3	1/3	1/2	1	2	6	7	0.935	0.114	0.824
C_5	1/4	1/4	1/3	1/2	1	5	6	0.611	0.075	0.571
C_6	1/8	1/8	1/7	1/6	1/5	1	4	0.205	0.025	0.229
C_7	1/9	1/9	1/8	1/7	1/6	1/4	1	0.145	0.018	0.141
								$\lambda_{max} = 6.910$	IC = – 0.015	CR = – 0.011

The alternatives pairwise comparisons, the vectors of priorities, the results of their multiplication Y_i, λ_{max}, CR and IC for each alternative are presented in table 5.

Alternatives:

A_1 - TECHNOVENT STANDARD;
A_2 - XPS TECHNONICOL CARBON ECO;
A_3 - LOGICPIR WALL;
A_4 - URSA GEO Universal plate;
A_5 - AKOTERM FLAX;
A_6 - AEROC EcoTerm Plus (D300)

The eigenvalue of the each matrix, IC and CR were calculated by the equations (2), (3) and (4), CR and IC are not exceed 10%.

Table 5. Calculating of the alternatives vectors of priorities

C_1	A_1	A_2	A_3	A_4	A_5	A_6	The rating of the eigenvector components by row	Alternative vector of priorities	Y_i	λ_{max}, CR, IC
A_1	1	1/2	1/3	1	1	6	1.000	0.130	0.784	λ_{max} = 6.091
A_2	2	1	1/2	2	2	7	1.743	0.226	1.374	
A_3	3	2	1	3	3	8	2.749	0.357	2.195	IC = 0.018
A_4	1	1/2	1/3	1	1	6	1.000	0.130	0.784	
A_5	1	1/2	1/3	1	1	6	1.000	0.130	0.784	CR = 0.015
A_6	1/6	1/7	1/8	1/6	1/6	1	0.209	0.027	0.169	
C_2	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	9	7	1	9	1	2.877	0.296	1.792	λ_{max} = 6.080
A_2	1/9	1	1/3	1/9	1	1/9	0.278	0.029	0.174	
A_3	1/7	3	1	1/7	3	1/7	0.545	0.056	0.354	IC = 0.016
A_4	1	9	7	1	9	1	2.877	0.296	1.792	
A_5	1/9	1	1/3	1/9	1	1/9	0.278	0.029	0.174	CR = 0.013
A_6	1	9	7	1	9	1	2.877	0.296	1.792	
C_3	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	5	5	1/5	1/3	2	1.222	0.129	0.804	λ_{max} = 6.414
A_2	1/5	1	1	1/9	1/7	1/4	0.304	0.032	0.201	
A_3	1/5	1	1	1/9	1/6	1/3	0.328	0.034	0.213	IC = 0.083
A_4	5	9	9	1	4	6	4.620	0.486	3.170	
A_5	3	7	6	1/4	1	4	2.239	0.236	1.507	CR = 0.067
A_6	1/2	4	3	1/6	1/4	1	0.794	0.083	0.519	
C_4	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	3	8	1/2	3	1	1.817	0.218	1.317	λ_{max} = 6.100
A_2	1/3	1	5	1/5	1	1/3	0.693	0.083	0.508	
A_3	1/8	1/5	1	1/9	1/5	1/8	0.203	0.024	0.154	IC = 0.020
A_4	2	5	9	1	5	2	3.107	0.373	2.297	
A_5	1/3	1	5	1/5	1	1/3	0.693	0.083	0.508	CR = 0.016
A_6	1	3	8	1/2	3	1	1.817	0.218	1.317	
C_5	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	1/3	1/2	1/6	1/3	1/6	0.340	0.041	0.296	λ_{max} = 6.431
A_2	3	1	2	1/3	1	7	1.552	0.189	1.211	
A_3	2	1/2	1	1/4	1/2	2	0.794	0.097	0.582	IC = 0.086
A_4	6	3	4	1	3	9	3.533	0.430	2.678	
A_5	3	1	2	1/3	1	7	1.552	0.189	1.211	CR = 0.069
A_6	6	1/7	1/2	1/9	1/7	1	0.435	0.053	0.452	
C_6	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	1	7	1	1/4	1	1.098	0.134	0.807	λ_{max} = 6.163
A_2	1	1	7	1	1/4	1	1.098	0.134	0.807	
A_3	1/7	1/7	1	1/7	1/9	1/7	0.189	0.023	0.149	IC = 0.033
A_4	1	1	7	1	1/4	1	1.098	0.134	0.807	
A_5	4	4	9	4	1	4	3.634	0.442	2.788	CR = 0.026
A_6	1	1	7	1	1/4	1	1.098	0.134	0.807	
C_7	A_1	A_2	A_3	A_4	A_5	A_6				
A_1	1	1/3	1/2	1/2	1/2	7	0.814	0.106	0.650	λ_{max} = 6.065
A_2	3	1	2	2	2	9	2.449	0.319	1.949	
A_3	2	1/2	1	1	1	8	1.414	0.184	1.108	IC = 0.013
A_4	2	1/2	1	1	1	8	1.414	0.184	1.108	
A_5	2	1/2	1	1	1	8	1.414	0.184	1.108	CR = 0.011
A_6	1/7	1/9	1/8	1/8	1/8	1	0.177	0.023	0.143	

The result of conducted hierarchical synthesis is presented in table 6.

Table 6. The results of the selecting of the most appropriate building thermal insulation material for residential buildings

Thermal insulation materials	Global priorities
TECHNOVENT STANDARD	0.181
XPS TECHNONICOL CARBON ECO	0.113
LOGICPIR WALL	0.141
URSA GEO Universal plate	0.294
AKOTERM FLAX	0.127
AEROC EcoTerm Plus (D300)	0.143

4. Discussion
Thus, the best option by the set of characteristics may be to consider the fiberglass plates GEO URSA Universal plate. Slabs made of basalt rock stonewool with a low-phenol binder TECHNOVENT STANDARD lose them only due to the higher average density and cost with little difference other technical characteristics. Rigid polyisocyanurate plates LOGICPIR WALL, linen fiber plates AKOTERM FLAX and AAC blocks AEROC EcoTerm Plus (D300) have approximately equal values of global priorities. The least successful of the above options can be considered the XPS TECHNONICOL CARBON ECO – it is flammable and combustible and has a low water vapor permeability, which limits its application scope, despite the low conductivity and the average density.

5. Conclusions
The proposed technique can be applied for selection of the most appropriate building material or technological equipment from the available options based on its qualitative and quantitative characteristics.

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