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 do 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-resistance, 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].

| Thermal insulating materials                  | Fire safety class | Average density, kg/m³ | Thermal conductivity, W/(m·°C) | Cost, RUB/m³ | Lifespan / warranty, years | Vapour permeability coefficient, mg/(m²·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/m³.

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 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].

| \( A_1 \) | \( A_2 \) | \( A_3 \) | \ldots | \( A_n \) |
|---|---|---|---|
| \( A_1 \) | \( w_1/w_1 \) | \( w_1/w_2 \) | \( w_1/w_3 \) | \ldots | \( w_1/w_n \) |
| \( A_2 \) | \( w_2/w_1 \) | \( w_2/w_2 \) | \( w_2/w_3 \) | \ldots | \( w_2/w_n \) |
| \( A_3 \) | \( w_3/w_1 \) | \( w_3/w_2 \) | \( w_3/w_3 \) | \ldots | \( w_3/w_n \) |
| \ldots | \( \ldots \) | \( \ldots \) | \( \ldots \) | \ldots | \( \ldots \) |
| \( A_n \) | \( w_n/w_1 \) | \( w_n/w_2 \) | \( w_n/w_3 \) | \ldots | \( w_n/w_n \) |

\( A_1, A_2, \ldots, A_n \) is the set of \( n \) elements and \( w_1, w_2, \ldots, w_n \) 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. \( w_i/w_i \) 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).

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 |
|------|---|------|-----------------------------------------------|---------------------|
|      |   |      | $\sqrt{\frac{w_1}{w_1} \times \cdots \times \frac{w_i}{w_i}} = a_i$ | $\frac{a_i}{\sum_{j=1}^{n} a_j} = x_i$ |
|      |   |      |                                              |                     |
|      |   |      | $\sqrt{\frac{w_n}{w_1} \times \cdots \times \frac{w_n}{w_n}} = a_n$ | $\frac{a_n}{\sum_{j=1}^{n} a_j} = x_n$ |

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

$$
\begin{pmatrix}
\frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\
\frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n}
\end{pmatrix} \begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix} =
\begin{pmatrix}
\frac{w_1}{w_1} x_1 + \frac{w_1}{w_2} x_2 + \cdots + \frac{w_1}{w_n} x_n = Y_1 \\
\frac{w_2}{w_1} x_1 + \frac{w_2}{w_2} x_2 + \cdots + \frac{w_2}{w_n} x_n = Y_2 \\
\vdots \\
\frac{w_n}{w_1} x_1 + \frac{w_n}{w_2} x_2 + \cdots + \frac{w_n}{w_n} x_n = Y_n
\end{pmatrix}
$$

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 $A'w' = \lambda_{max}w'$, $A' = (a_{ij})$, where $\lambda_{max}$ 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):

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

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

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

where $\lambda_{max}$ – eigenvalue of the matrix, $n$ – the number of compared elements.

$$CR = IC/RI,$$

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*K);
- $C_2$ - fire safety class;
- $C_3$ - vapour permeability coefficient, mg/(m*K*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%.

| $C_i$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | 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 $Y_i$, $\lambda_{max}$, 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%. 
The rating of the components by row

| \( C_i \) | \( A_i \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_6 \) | Alternative vector of priorities | \( Y_i \) | \( \lambda_{max}, \ CR, \ IC \) |
|---|---|---|---|---|---|---|---|---|---|
| \( A_1 \) | 1 | 1/2 | 1/3 | 1 | 1 | 6 | 1.000 | 0.130 | 0.784 | \( \lambda_{max} = 6.091 \) |
| \( A_2 \) | 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 |  |

\[
C_1 \quad A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \quad A_6
\]

| \( C_i \) | \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_6 \) | Alternative vector of priorities | \( Y_i \) | \( \lambda_{max}, \ CR, \ IC \) |
|---|---|---|---|---|---|---|---|---|---|
| \( A_1 \) | 1 | 9 | 7 | 1 | 9 | 1 | 2.877 | 0.296 | 1.792 | \( \lambda_{max} = 6.080 \) |
| \( A_2 \) | 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 |  |

\[
C_2 \quad A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \quad A_6
\]

| \( C_i \) | \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_6 \) | Alternative vector of priorities | \( Y_i \) | \( \lambda_{max}, \ CR, \ IC \) |
|---|---|---|---|---|---|---|---|---|---|
| \( A_1 \) | 1 | 5 | 5 | 1/5 | 1/3 | 2 | 1.222 | 0.129 | 0.804 | \( \lambda_{max} = 6.414 \) |
| \( A_2 \) | 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 |  |

\[
C_3 \quad A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \quad A_6
\]

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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