

# Using of a weighted directed acyclic graph for major repairs of real estate objects: the optimal combination of energy-efficient measures introduction

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**Abstract.** Energy consumption analysis by regions of the world for the period from 2005 to 2019 showed that the growth of energy consumption is only increasing every year and requires certain energy-efficient measures. The largest energy consumption is in the construction sector, namely in residential buildings, which is associated with the large cities urbanization. Energy consumption depends not only on the energy efficiency of the temperature and lighting control systems, but also on the efficiency of the buildings in which they operate. Based on this, the housing stock of the city of Voronezh, which was conditionally divided into "old apartment buildings" and "new apartment buildings" (depending on the building period) was considered. Multi-apartment buildings were considered, taking into account various characteristics in order to identify the actual characteristics that affect energy consumption. Based on the data obtained, a statistical analysis of energy consumption in old apartment buildings and new ones, respectively, was carried out. On the basis of the research an algorithm was proposed for the energy-efficient measures introduction when planning major repairs in apartment buildings (AB) using a weighted directed acyclic graph.

## 1 Introduction

Energy access is a key element of human well-being, economic development, and the fight against high costs. Ensuring adequate access for all is an ongoing and urgent global development challenge. Energy resources include oil, natural gas, bituminous and brown coal, oil shale, peat, uranium (lithosphere resources, practically non-renewable), wood (biosphere resources, renewable), hydropower (hydrosphere resources, inexhaustible), etc.

The dynamics of energy consumption in the world has a consistently positive trend. The growing institutional contradictions between oil and natural gas consumers and producers is accompanied by an increase in demand for energy resources around the world. In recent years, many analysts have determined the danger of another wave of growth in energy

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consumption. This growth is associated with an increase in the population, rapid industrialization of some countries (India, China, etc.) and, as a consequence, an increase in the amount of consumed resources. Thus, the issue of limited resources is relevant at the moment [1,2].

To date, the main regularity in the structure energy consumption throughout the world is the change in the amount of energy consumed and is presented in table. 1 [2].

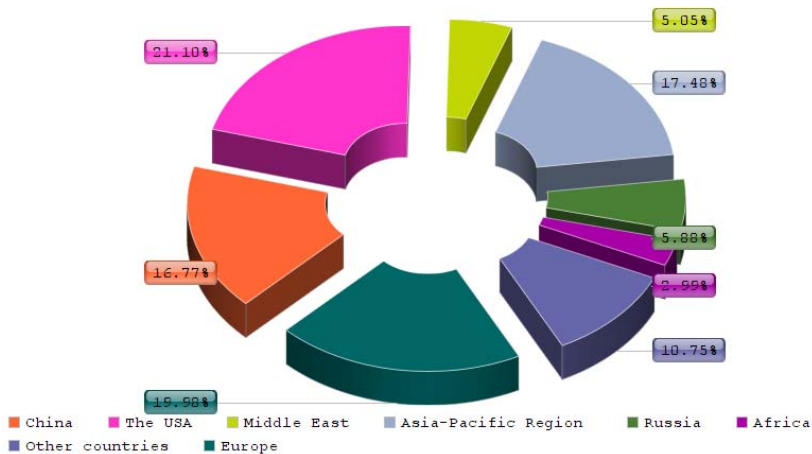
**Table 1.** Energy consumption in the regions of the world in 2005-2019, million toe

	2005	2010	2015	2019
<b>Europe</b>	2 175.5	2 124.6	1 996.8	2 002
<b>China</b>	1 826	2 519.2	3 037.7	3 414
<b>The USA</b>	2 297.4	2 223.3	2 213.2	2 261
<b>Middle East</b>	549.3	709.8	843.7	926.2
<b>Asia-Pacific Region (except China)</b>	1 903.1	2 182.3	2 438	2 738
<b>Russia</b>	640.6	669.3	675.4	712
<b>Africa</b>	325.5	383.8	430.1	474.6
<b>Other countries</b>	1 170.5	1 287.6	1 410.7	1 418.4
<b>Entire world</b>	10 887.9	12 099.9	13 045.6	13 946.2

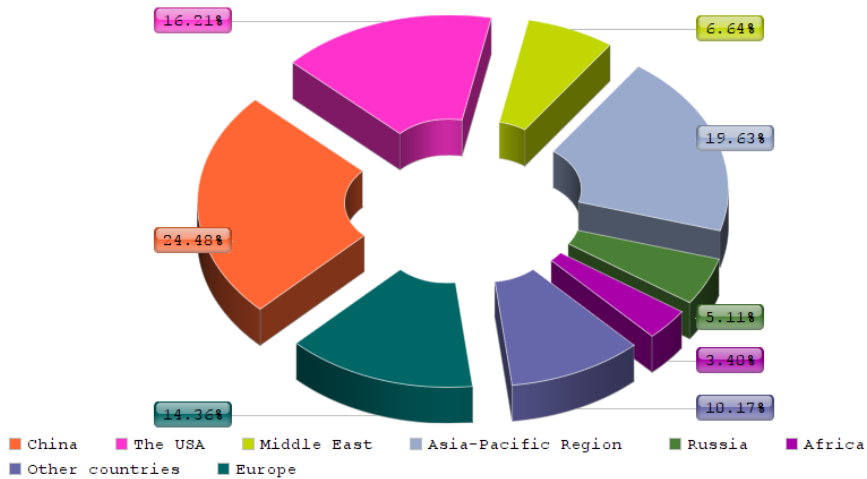
**Source:** BP Statistical Review of World Energy

Having Considered the structure of the world energy consumption, we can note an uneven change in the consumption of energy resources in different regions. Thus, a rapid growth in consumption was noted in developing countries (China and the Asia-Pacific region). The total part of energy consumption in these regions was 44% in 2019, which is 10% more than in 2005 (Fig. 1, Fig. 2).

The global use of energy resources can be attributed to construction. This is due to the fact that we spend most of our life in buildings. In recent decades, there has been rapid urbanization in all regions of the world. As cities begin to grow rapidly, construction volumes increase and as a result there is an increase in demand for energy resources (heating, cooling and lighting).



**Fig. 1.** Structure of energy consumption by regions of the world in 2005



**Fig. 2.** Structure of energy consumption by regions of the world in 2009

Thus, the main final energy consumption is for heating, cooling and lighting of premises. To reduce energy consumption in buildings, it is necessary to use energy efficient control systems and efficient materials in the construction and renovation of buildings [3].

Rapid urbanization and the increasing rate of consumption and extraction of energy resources require urgent action. These measures are advisable to apply in the residential buildings construction, because they account for most of the energy consumed.

## 2 Materials and technique

Multi-storey residential buildings are among the most dominant types of housing in the world. The failing housing stock in the Russian Federation is growing rapidly every year, and therefore this problem is urgent.

To solve the problem of limited energy resources, measures are being taken to reduce greenhouse gas emissions by improving and adjusting the regulatory framework and thermal modernization of old apartment buildings (AB). This is due to the fact that old residential buildings do not meet energy efficiency requirements and were built in accordance with outdated building codes. So from October 1, 2003, a new SNiP 23-02-03 "Thermal protection of buildings" was put into effect to replace the SNiP II-3-79 "Construction heat engineering", which has lost its relevance. In accordance with this regulatory documentation, it is envisaged to introduce new indicators of buildings energy efficiency in the design, construction and operation of buildings. Despite the introduction of new building codes and regulations, energy consumption in residential buildings has not decreased, and CO<sub>2</sub> emissions have not decreased.

Despite the government's efforts and the proposed energy saving technologies, there are limitations in terms of designing existing strategies for the reconstruction of old residential buildings in order to reduce the amount of energy consumed, namely [4,5]:

1. The focus is on economic gains rather than reducing energy consumption or CO<sub>2</sub> emissions.

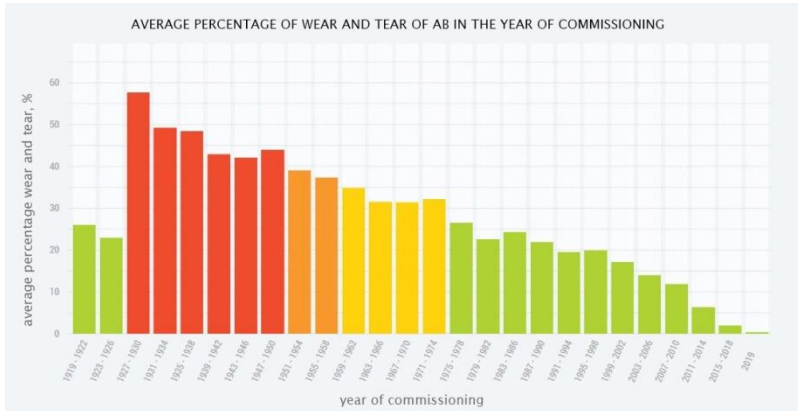
2. The existing regulatory framework using energy efficient technologies does not sufficiently cover old apartment buildings that need major repairs.

In various periods of time during major repairs the design features of old apartment buildings were repeatedly changed, which referred to outdated regulatory documents. Thus,

the existing regulatory framework does not take into account the transformation of the old ABs characteristics.

Investigating the housing stock in Voronezh, we conditionally divided it into "old apartment buildings" built before 2003 and "new apartment buildings" built after 2003 (in connection with the introduction of SNiP 23-02-03 "Thermal protection of buildings" since 2003).

By analyzing previous regulatory documents and studying the history of domestic housing construction, the distinctive characteristics of "old apartment buildings" in the period from the 1930s were identified. (fig. 3).



**Fig. 3.** Average percentage of apartment buildings wear and tear by the year of commissioning, Voronezh [6]

As mentioned above, the following characteristics of apartment buildings were transformed with changes in public preferences: number of storeys, load-bearing structures material, and layout scheme. It is also worth noting the change in the area of multi-apartment buildings depending on the layout scheme. One of the reasons for changing the characteristics of multi-family residential buildings is also the improvement of building standards and technologies.

Based on this, the thermal conditions of building enclosing structures were measured by years of construction, which were separated by the revision of building codes: up to 1955, 1955 – 1963, 1963-1972, 1972-1979, 1979 – 2003 and after 2003. In addition, three types of heating systems were taken into account.

In view of these transformations, apartment buildings with different characteristics were examined to identify the actual characteristics affecting energy consumption. Table 2 shows how the structural features of buildings changed.

**Table 2.** Comparative analysis of the structural characteristics of buildings

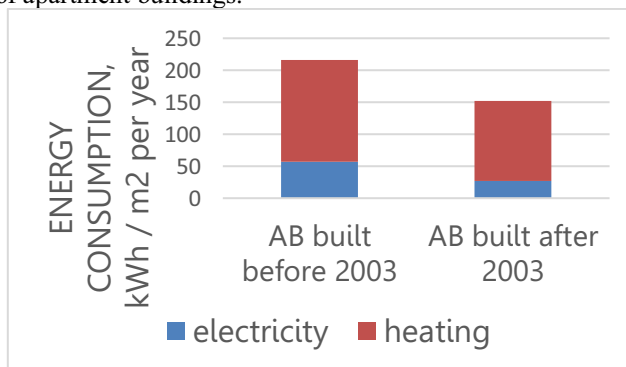
Characteristic of apartment building	Building codes and regulations/ Validity period					
	not provided	SNiP II-V.3/ 1955-1963	SNiP II-A. 7-62/ 1963-1972	SNiP II-A. 7-71/ 1972-1979	SNiP II-3-79/ 1979-2003	SNiP 23-02-2003 / 2003 and later

Heating system	+	+	+	+	+	+	centralized
	-	-	-	+	+	+	decentralized
	-	-	-	-	+	+	individual decentralized
Structural material of load-bearing walls	+	+	+	-	-	-	brick
	-	+	+	+	+	+	concrete panel
	-	-	-	-	+	+	monolith
Number of storeys	+	+	-	-	-	-	low-rise (1-2 fl.)
	-	+	+	+	-	-	mid-rise (3-5 fl.)
	-	-	-	+	+	+	multi-storey (6 or more fl.)
Building layout scheme	+	+	-	-	-	-	corridor
	-	-	-	-	-	-	gallery
	-	-	+	+	+	+	sectional
	-	-	-	-	+	+	centric

The characteristics considered are necessary to quantify energy consumption (heating and electricity supply). Based on the data obtained, a statistical analysis of energy consumption in old multi-apartment buildings and new ones was carried out.

18 old apartment buildings were selected for analysis. To select residential buildings, four parameters were taken into account: year of construction; number of floors; availability of data on energy consumption, material of supporting structures. In this case, apartment buildings built between 1946 and 1983 were considered. Information on energy consumption was taken into account for 2016 and was obtained from open sources [7]. The collected data for electricity and heating has been converted to kWh / m<sup>2</sup> per year. Buildings that were built after 2003 and selected for comparison of energy consumption in old apartment buildings because they are considered to be relatively energy efficient. The data on electricity and heat consumption were collected using the same method as for old apartment buildings.

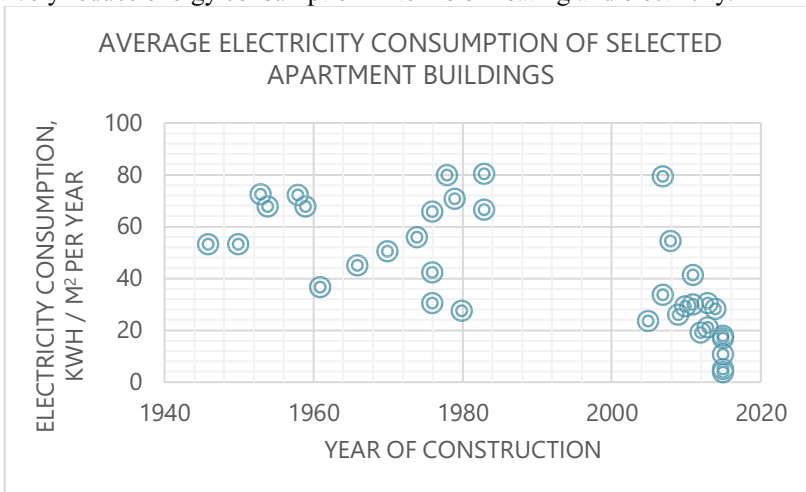
In Fig. 4, you can see the average energy consumption in old apartment buildings, which is 212 kWh / m<sup>2</sup> per year and 152 kWh / m<sup>2</sup> per year in new apartment buildings, respectively. This result shows the influence of design features on the energy consumption of both groups of apartment buildings.



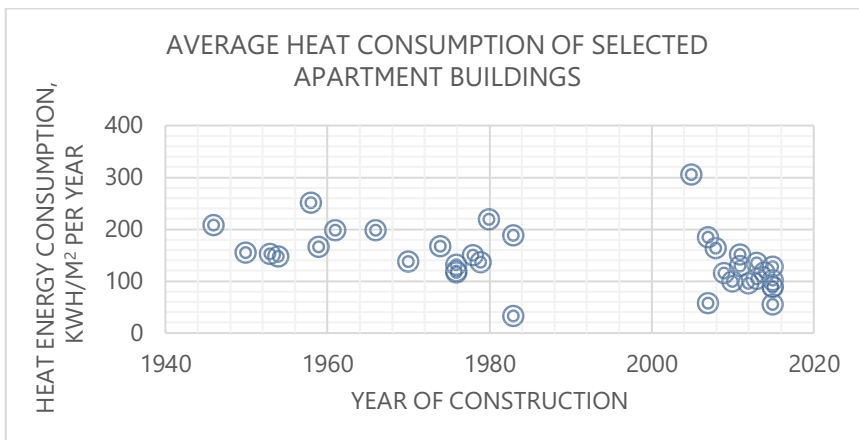
**Fig. 4.** Average energy consumption in the selected apartment buildings (by years of construction)

These patterns are shown in Fig. 5 and 6. The average energy consumed for space heating in old ABs has decreased over the years of their construction. Old ABs built before 1983, with the exception of some, consumed more energy for heating than the average of 186 kWh / m<sup>2</sup> per year. None of the buildings built between 2003 and 2015 consumed more than average heating energy. These results indicate that apartment buildings built after 2003 have been able to effectively reduce energy consumption for heating.

Electricity consumption for the period under review has also decreased. This can be explained by the use of modern household appliances that consume significantly less electricity than their ten-year-old predecessors. Overall, apartment buildings have been able to effectively reduce energy consumption in terms of heating and electricity.



**Fig. 5.** Electricity consumption by apartment buildings by year of construction



**Fig. 6.** Heat energy consumption by apartment buildings by year of construction

### 3. Findings

The noted ABs design features make it possible to select the most energy efficient list of measures and their sequence when carrying out major repairs [8]:

- increase in thermal resistance of enclosing structures due to: glazing of balconies and loggias, elimination of cold joints in the walls and in the window sashes junction, thermal insulation of external walls, technical floor, roof, ceilings above the basement with modern energy-efficient materials, etc.;
- increasing the energy efficiency of the heating system due to: additional heating and water heating when using solar collectors and heat accumulators, installing thermostats and temperature controllers on radiators, switching over to an individual apartment heating scheme during repairs, etc.;
- energy savings through the use of energy-efficient home appliances of A + and A ++ classes, commissioning of solar panels and systems with the installation of motion sensors when servicing common property, etc.

For a more efficient operation of the proposed approach and a more accurate assessment of the housing stock state, it is necessary to use an optimal combination of consistently implemented energy-efficient measures, presented in the form of a weighted directed acyclic graph (the relationship between the AB and planned energy-efficient measures).

Taking into account the resource possibilities during the AB major repair, we determine the optimal combination of the consistent implementation of energy efficient measures. Let us represent in the form of a weighted directed acyclic graph the connection between the AB and the energy efficiency measures planned for implementation.

We represent the structure of the graph in the form of a square adjacency matrix in a binary relation. The adjacency elements of the digraph matrix are determined by the formula [9,10]:

$$a_{ij} \begin{cases} 1, \text{ if } (v_i, v_j \in E) \\ 0, \text{ if } (v_i, v_j \notin E) \end{cases} \quad (1)$$

where  $V = \{v_1, v_2, \dots, v_n\}$  is the set of digraph vertices;

$E = \{e_1, e_2, \dots, e_{n-1}\}$  is the set of digraph edges.

Suppose there are  $m$  apartment buildings and  $n$  energy saving measures. It is necessary to determine the resource capabilities of the overhaul. To determine resource capabilities, we create an adjacency matrix  $A$  ( $n \times m$ ) according to the following indicators:

1. According to the condition of resource limitation for each AB (where 1 is the necessary resources, 0 is the resources are limited) (2):

$$A_1 = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \quad (2)$$

2. According to the costs of the energy efficient measures implementation (where 1 is the minimum cost, 0 is the cost that exceeds the permissible) (3):

$$A_2 = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \quad (3)$$

3. According to the cumulative effect from the introduction of energy efficient measures (4):

$$A_3 = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 \end{bmatrix} \quad (4)$$

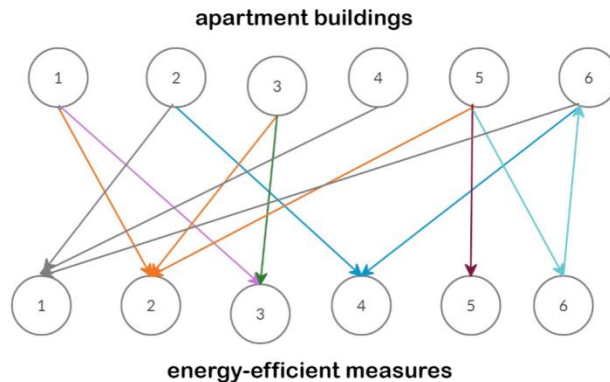
4. Depending on the "rebound effect" [11,12] (where 1-the rebound effect is not present or actually coincided with the expected, 0- the actual effect exceeded the expected) (5):

$$A_4 = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (5)$$

By combining the obtained matrices A1, A2, A3, A4, we determine the resource possibilities for the implementation of energy-efficient measures during the AB major repair (6).

$$A = \begin{bmatrix} 0101 & \underline{1111} & 1011 & \underline{1111} & 1110 & \underline{1111} \\ \underline{1111} & 1010 & \underline{1111} & 0010 & \underline{1111} & 0001 \\ \underline{1111} & 0001 & \underline{1111} & 1100 & 0000 & 0111 \\ 0110 & \underline{1111} & 0100 & 1101 & 1101 & \underline{1111} \\ 0010 & 1000 & 1100 & 0111 & \underline{1111} & 1001 \\ 0001 & 0110 & 1011 & 0001 & \underline{1111} & \underline{1111} \end{bmatrix} \quad (6)$$

The elements of matrix A, consisting of ones, determine the optimal combination of the possibility of introducing energy-efficient measures when carrying out major repairs in existing apartment buildings with minimal costs. Based on the obtained combinations, we construct a digraph showing the relationship between the planned energy-efficient measures in the apartment building [13]. The number of energy saving measures planned for implementation may be two or more. The order of implementation of energy efficient measures is determined depending on the economic assessment of the effectiveness of the implementation (Fig. 7).



**Fig. 7.** Implementation of the planned energy-efficient measures during major repairs in apartment buildings



To assess economic efficiency, it is necessary to determine a number of indicators, such as: the payback period of each measure, the net income received from the implementation of energy efficient measures.

The indicator of efficiency from the introduction of energy efficient measures can be presented in general as [14,15]:

$$E_e = \frac{Q_{i0} - Q_{i1}}{C_i} \rightarrow \max \quad (7)$$

where  $Q_{i0}$  is the energy consumption before the introduction of energy-saving technology;

$Q_{i1}$  is the energy consumption after the introduction of energy-saving technology;

$C_i$  is the costs of implementing energy-saving technology.

A payback period (PP) was also invested in the building, excluding discounted income, determined by the formula (8):

$$PP = \frac{Inv}{E_t} \quad (8)$$

where  $I_{nv}$  is the initial investment in the project;

$E_t$  is the savings in time period  $t$ .

The calculation of the payback period for the implementation of energy-saving measures is not correct enough without taking into account discounting (DPP), which is determined by the formula (9):

$$DPP = Inv / \frac{\sum_{i=1}^n (E_i - C_i)}{(1+r)^i} \quad (9)$$

where  $I_{nv}$  is the initial investment in the project;

$E_i$  is the savings in time period  $i$ ;

$C_i$  is the savings in time period  $i$ ;

$R$  is the discount rate;

$I$  is the number of periods.

The universal financial and economic indicator of the assessment from the implementation of the measure is the net present value (NPV). It takes into account not only the costs throughout the life cycle, but also the effect of the implementation of activities.

The net present value (NPV) represents the amount of net savings for the entire calculation period, taking into account the value of money over time (10).

$$NPV = \sum_{i=1}^T \frac{CF^+(t)}{(1+r)^i} - \sum_{i=1}^T \frac{CF^-(t)}{(1+r)^i} \quad (10)$$

Where  $CF^+$  is the cash flow in each specific period  $t$  ( $t= 1 \dots n$ );

$CF^-$  is the cash outflow in each specific period  $t$  ( $t= 1 \dots n$ );

$T$  is the billing period.

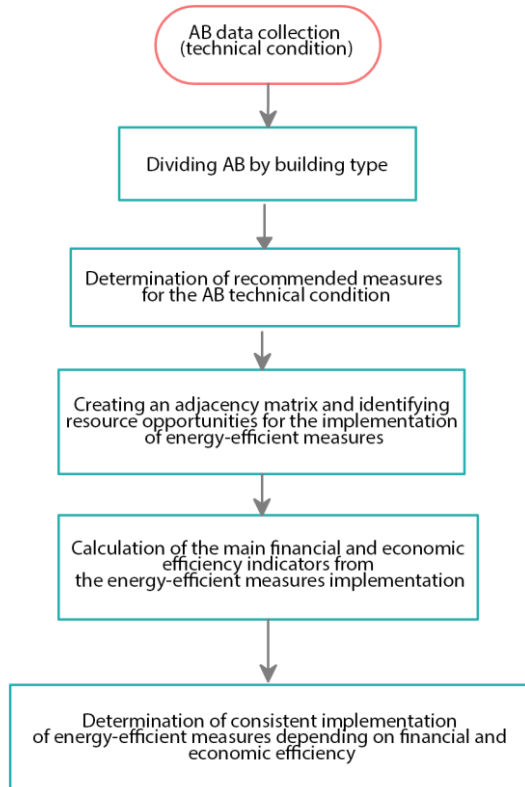
$I$  is the current year;

$r$  is the discount rate.

Having performed calculations according to the formula (9), we will have the following indicators:  $NPV \geq 0$  the project is considered effective;  $NPV \leq 0$  the project is accordingly ineffective [16,17].

## Conclusion

The algorithm for the implementation of energy efficient measures when planning a major repair in an AB is shown in Fig. 8 [13].



**Fig. 8.** Algorithm for the implementation of energy efficient measures when carrying out major repairs in an apartment building.

Thus, it is necessary to take into account the efficiency of energy efficient measures not only depending on the payback period, but also on the time of energy efficient measures implementation and the "rebound effect". The sooner the necessary energy efficiency measures are introduced, the faster the result from the implementation will be obtained. This is due to the emergence of a cumulative effect. Therefore, it is advisable to take into account losses during the delayed introduction of an energy efficient measure which leads to a decrease in the cumulative effect.

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