Reconstruction of the gray belt objects based on energy efficiency clusters

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Abstract. Objects redevelopment methods of the “gray belt” - industrial areas surrounding the historical district of St. Petersburg, Russia - have been considered. Information about 45 objects located in different administrative districts of the city was collected. Factors of physical wear (wear of floors, walls, roofs, types of building structural system) have been chosen as a criteria for clustering. As a result of the study, SOMs with different learning parameters were created as a result of the study. Energy efficiency calculations for two clusters were made with the selection of modern materials. Recommendations for the reconstruction according to the parameters of physical wear are given.

1 Introduction

The issue of the development of old industrial zones is relevant today. The reorganization of industrial buildings and their territories can create new places of attraction for visitors and citizens. This will help to stimulate the economics, disperse the tourist centre and reduce the traffic load [1-5]. Also the reorganization of this area will expand the network of polycentres with a developed horizontal infrastructure. This will contribute to improving the quality of life thanks to a reasonable and comfortable arrangement of the territory, creating an attractive, balanced environment for work, living and recreation of the citizens [6-11].

The industrial zone of St. Petersburg, Russia or the "gray belt", is the largest reserve for urban development near the historic centre of the city. The area of industrial buildings in St. Petersburg is about 50 million m². According to various estimates, this zone occupies about 40% of the total area of the city.

Industrial territories are located in 12 administrative districts of St. Petersburg. The gray belt is outlined by the coast of the Neva Bay, it includes a port complex in the southern part of Kanonersky Island. It includes industrial and public business buildings in Kirovsky, Moskovsky, Frunzensky and Nevsky districts, within the territory outlined by the Obvodny Canal and Leninsky Prospekt, Tipanova Street and Slavy Prospekt. Also there are industrial buildings remained on the right bank of the Neva from Narodnaya Street to Energetikov

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Prospekt in the southern part of Krasnogvardeisky district. At the moment, most of the objects of the «Gray belt» are in need of reconstruction.

Achieving the level of quality and comfort of buildings, the standards of thermal protection during the reconstruction is much more difficult than with new construction. For example, it is difficult to significantly change the planning decisions, the material of the building envelope, etc.

From the point of view of architectural and construction solutions, the main indicator of energy efficiency of a building is resistance to heat transfer of building envelope. This parameter determines the temperature of the surfaces of the building envelope, affecting the feeling of comfort.

The method of calculating this indicator has changed significantly since the 1970s. In 2003, amendments appeared in the thermotechnical standard, which consider the climatic features of various regions of the country.

The purpose of this work is to create clusters according to the characteristics of physical wear and type of construction, to provide each cluster with calculation of energy efficiency during the reconstruction [12 - 14].

Tasks:
- to identify gray belt objects;
- to determine the types of structures for each object;
- to determine the wear of structures for each object;
- to group the gray belt objects into clusters;
- to carry out the calculation of energy efficiency during the reconstruction of each cluster.

2 Materials and Methods

To determine the effective strategy of redevelopment of gray belt objects, it is necessary to develop an approach for classifying objects included in these zones. In this article, it is proposed to use self-organizing maps for clustering objects.

A self-organizing map (SOM) or self-organizing feature map (SOFM) – is a type of artificial neural network (ANN), that is trained using uncontrollable learning to produce a low-dimensional (typically two-dimensional) discretized representation of the input space of the training samples, called a map, and therefore it is a method of reducing the dimension. They were developed in 1982 by Tuevo Kohonen, an honorable professor of the Academy of Finland [15]. Self-organizing map (SOM) – is an efficient tool for neural network modelling for visualization and generalization of multidimensional data. It is suitable for solving complex problems like process analysis, machine perception, control and information transfer [16].

The Self-Organizing Map algorithm can be divided into 6 steps [15]:
1. The weights of each node are determined.
2. The input vector is randomly selected from the training data set and presented to the network.
3. Each node of the network tests for matching to the input vector. Winning node becomes «Best Matching Unit» (BMU).
4. The range of the BMU is calculated. This value starts with the highest one. It is usually set as the network radius, decreasing with each iteration.
5. All nodes found in the radius of the «Best Matching Unit» neuron, calculated in the item 4, are configured so that they are more similar to the input vector. His weights change more if it’s closer to the BMU.
6. Repeat item 2 for N iterations.
45 buildings of the gray belt located in different parts of the city were selected as objects of research [17]. 4-5 objects were selected from each district for further research. The distribution of the researched objects by districts is shown in Figure 1.

Fig. 1. Number of research objects by districts

The following information was collected for each object:
1. Physical wear characteristics (roof wear, floor wear, wall wear).
2. Type of construction (roof materials, floor materials and wall materials). These characteristics are shown in Table 1.

Table 1. Types of constructions and physical wear

| №  | Symbol 1 | District       | Roof                              | Wear of roof, % | Floors                   | Wear of floors, % | Walls                  | Wear of walls, % |
|----|----------|----------------|-----------------------------------|-----------------|--------------------------|-------------------|-----------------------|------------------|
| 1  | V-1      | Vasileostrovsky| Bitumen felt with sealant compound| 75              | Reinforced concrete shell| 60                | Brick wall            | 55               |
| 2  | V-2      | Vasileostrovsky| Roofing steel on timber rafters   | 50              | Timber floor, brick arches| 50                | Brick wall            | 40               |
| 3  | V-3      | Vasileostrovsky| Roofing steel on timber rafters   | 60              | Precast reinforced concrete floor slabs on steel beams | 70 | Brick wall with timber partitions | 60 |
| 4  | V-4      | Vasileostrovsky| Bitumen felt with sealant compound| 15              | Precast reinforced concrete floor slabs on steel truss | 15 | Brick wall             | 10               |
| 5  | V-5      | Vasileostrovsky| Bitumen felt with sealant compound on | 15              | Precast reinforced concrete floor | 15 | Brick wall             | 10               |
| №  | Symbol  | District    | Roof                          | Wear of roof, % | Floors       | Wear of floors, % | Walls                          | Wear of walls, % |
|----|---------|-------------|-------------------------------|----------------|--------------|------------------|--------------------------------|-----------------|
| 6  | P-1     | Petrogradsky| Built-up roofing; bitumen felt with sealant compound, metal roof | 50             | Brick arches on steel beams; cast reinforced concrete slab | 45               | Brick wall; reinforced concrete and steel columns | 45              |
| 7  | P-2     | Petrogradsky| Iron roof                     | 30             | Timber floor on timber beams | 40               | Plastered brick wall              | 30              |
| 8  | P-3     | Petrogradsky| Metal roof                    | 10             | Plastered timber floor on steel beams | 35               | Plastered brick wall              | 30              |
| 9  | K-1     | Kalininsky  | Roofing steel on timber rafters | 40             | Steel beams with timber beams; cast reinforced concrete slab | 40               | Brick wall with ceramic wall tile and timber partitions | 30              |
| 10 | K-2     | Kalininsky  | Roofing steel on timber rafters | 45             | Timber floor | 45               | Plastered brick wall with timber partitions | 35              |
| 11 | K-3     | Kalininsky  | Roll roofing                   | 50             | Cast reinforced concrete slab and steel beams | 50               | Brick wall; reinforced concrete and steel columns | 50              |
| 12 | K-4     | Kalininsky  | Steel sheet                   | 25             | Precast reinforced concrete floor slabs | 30               | Plastered brick wall, coated with paint | 40              |
| 13 | Kr-1    | Krasnogvardeysky | Metal roof              | 15             | Metal                  | 15               | Metal walls                    | 15              |
| 14 | Kr-2    | Krasnogvardeysky | Iron roof on timber rafters  | 45             | Precast reinforced concrete floor slabs | 35               | Brick wall                      | 35              |
| 15 | Kr-3    | Krasnogvardeysky | Iron roof on timber rafters  | 40             | Reinforced concrete beams with slag block | 40               | Brick wall                      | 40              |
| 16 | Kr-4    | Krasnogvardeysky | Bitumen felt with sealant compound on reinforced concrete roof | 35             | Precast reinforced concrete floor slabs | 20               | Brick wall with reinforced concrete | 20              |
| №  | Symbol | District      | Roof                                           | Wear of roof, % | Floors                                     | Wear of floors, % | Walls                              | Wear of walls, % |
|----|--------|---------------|------------------------------------------------|-----------------|--------------------------------------------|-------------------|-----------------------------------|------------------|
| 17 | Kr-5   | Krasnogvardeysky | Bitumen felt with sealant compound on reinforced concrete roof slab | 40              | Precast reinforced concrete floor slabs    | 30                | Brick wall with timber partitions | 65               |
| 18 | N-1    | Nevsky        | Roll roofing                                    | 30              | Precast reinforced concrete floor slabs    | 15                | Brick wall                        | 15               |
| 19 | N-2    | Nevsky        | Roll roofing                                    | 20              | Precast reinforced concrete floor slabs    | 15                | Brick wall with reinforced concrete panel | 15               |
| 20 | N-3    | Nevsky        | Bitumen felt with sealant compound on reinforced concrete roof slab; metal roof | 40              | Precast reinforced concrete floor slabs on steel truss | 25                | Brick wall with drywall partitions | 25               |
| 21 | N-4    | Nevsky        | Metal roof                                      | 25              | Precast reinforced concrete floor slabs    | 15                | Precast steel structures          | 15               |
| 22 | N-5    | Nevsky        | Roll roofing                                    | 20              | Precast reinforced concrete floor slabs    | 15                | Claydite concrete blocks; brick wall | 15               |
| 23 | F-1    | Frunzensky    | Iron roof on timber rafters/on reinforced concrete roof slab | 10              | Precast reinforced concrete floor slabs    | 10                | Plastered brick wall              | 10               |
| 24 | F-2    | Frunzensky    | Roll roofing                                    | 40              | Timber rafters; concrete arches on steel beams | 40                | Plastered brick wall              | 40               |
| 25 | F-3    | Frunzensky    | Bitumen felt with sealant compound on reinforced concrete roof slab | 15              | Precast reinforced concrete floor slabs    | 15                | Brick wall                        | 15               |
| №  | Symbol | District      | Roof                                      | Wear of roof, % | Floors                        | Wear of floors, % | Walls                                      | Wear of walls, % |
|----|--------|---------------|-------------------------------------------|-----------------|-------------------------------|-------------------|-------------------------------------------|------------------|
| 26 | F-4    | Frunzensky    | Bitumen felt with sealant compound on reinforced concrete roof slab | 25              | Precast reinforced concrete floor slabs | 20                | Brick wall with face brick; reinforced concrete columns | 20               |
| 27 | F-5    | Frunzensky    | Iron roof on timber rafters               | 40              | Precast reinforced concrete floor slabs | 35                | Brick wall with timber partitions          | 45               |
| 28 | M-1    | Moskovsky     | Roll roofing                              | 35              | Precast reinforced concrete floor slabs | 25                | Brick wall                                | 50               |
| 29 | M-2    | Moskovsky     | Galvanized steel sheet on timber rafters  | 35              | Timber floor on steel beams    | 40                | Brick wall with timber partitions          | 40               |
| 30 | M-3    | Moskovsky     | Metal roof on timber rafters              | 30              | Timber floor on timber beams   | 40                | Brick wall                                | 40               |
| 31 | M-4    | Moskovsky     | Roll roofing                              | 15              | Precast reinforced concrete floor slabs | 10                | Brick wall, wall panel                     | 15               |
| 32 | M-5    | Moskovsky     | Steel on timber rafters                   | 30              | Steel beams with concrete beams | 30                | Brick wall with timber partitions          | 30               |
| 33 | Kir-1  | Kirovsky      | Bitumen felt with sealant compound        | 35              | Precast reinforced concrete floor slabs | 25                | Brick wall                                | 25               |
| 34 | Kir-2  | Kirovsky      | Bitumen felt with sealant compound on reinforced concrete roof slab | 40              | Precast reinforced concrete floor slabs | 35                | Brick wall                                | 45               |
| 35 | Kir-3  | Kirovsky      | Bitumen felt with sealant compound on reinforced concrete roof slab | 30              | Precast reinforced concrete floor slabs | 20                | Claydite concrete blocks; brick wall with ceramic wall tile | 20               |
| 36 | Kir-4  | Kirovsky      | Bitumen felt with sealant compound        | 25              | Precast reinforced concrete floor slabs | 30                | Brick wall; reinforced concrete columns    | 25               |
| 37 | A-1    | Admiralty     | Slate on timber rafters                   | 40              | Timber floor on timber beams   | 45                | Plastered brick wall                      | 45               |
| №   | Symbol | District | Roof                          | Wear of roof, % | Floors                       | Wear of floors, % | Walls                        | Wear of walls, % |
|-----|--------|----------|-------------------------------|-----------------|------------------------------|------------------|------------------------------|------------------|
| 38  | A-2    | Admiralty| Metal roof                    | 40              | Reinforced concrete floor    | 40               | Brick wall                   | 40               |
| 39  | A-3    | Admiralty| Roll roofing                  | 45              | Reinforced concrete floor    | 45               | Brick wall                   | 50               |
| 40  | A-4    | Admiralty| Iron roof                     | 40              | Reinforced concrete floor    | 40               | Concrete wall with reinforced concrete frame | 40               |
| 41  | A-5    | Admiralty| Iron roof on timber rafters   | 40              | Steel beams with timber beams| 30               | Brick wall with timber partitions | 30               |
| 42  | T-1    | Tsentralny| Metall roof on timber rafters | 20              | Timber floor, reinforced concrete floor | 30               | Brick wall                   | 25               |
| 43  | T-2    | Tsentralny| Built-up roofing              | 30              | Reinforced concrete floor    | 20               | Brick wall                   | 25               |
| 44  | T-3    | Tsentralny| Built-up roofing              | 30              | Reinforced concrete floor    | 20               | Brick wall                   | 25               |
| 45  | T-4    | Tsentralny| Galvanized steel sheet on timber rafters | 30              | Plastered timber floor       | 40               | Brick wall with timber partitions | 40               |

3 Results

Total selection of the objects were 30 buildings of Saint-Petersburg industrial areas after pre-processing of the data and evaluation of their quality in the software named Deductor. The indicators of physical wear and types of structures with the extreme values and emissions were considered. Objects with extreme values were excluded from research.

The program Deductor analyzed the factors of physical wear. The results of the analysis are shown in Figure 2. The x-axis shows the values of each test criteria. The total number of clusters is seven (Table 2).
Fig. 2. Self-organizing map for physical wear characteristics

| Cluster | Symbol | Average roof wear, % | Average floor wear, % | Average wall wear, % |
|---------|--------|----------------------|-----------------------|---------------------|
| 7       | Kr-1   | 20                   | 15                    | 15                  |
|         | N-1    |                      |                       |                     |
|         | N-2    |                      |                       |                     |
|         | N-4    |                      |                       |                     |
|         | N-5    |                      |                       |                     |
| 6       | N-3    | 35                   | 23                    | 25                  |
|         | Kir-2  |                      |                       |                     |
|         | T-2    |                      |                       |                     |
|         | T-3    |                      |                       |                     |
| 5       | Kir-4  | 23                   | 30                    | 25                  |
|         | T-1    |                      |                       |                     |
|         | P-3    |                      |                       |                     |
| 4       | K-4    | 33                   | 40                    | 40                  |
|         | Kr-3   |                      |                       |                     |
|         | F-2    |                      |                       |                     |
|         | M-2    |                      |                       |                     |
|         | M-3    |                      |                       |                     |
| 3       | P-2    | 35                   | 35                    | 30                  |
|         | K-1    |                      |                       |                     |
|         | V-5    |                      |                       |                     |
|         | A-5    |                      |                       |                     |
| 2       | P-1    | 40                   | 40                    | 47                  |
|         | K-3    |                      |                       |                     |
|         | F-5    |                      |                       |                     |
|         | M-1    |                      |                       |                     |
| 1       | V-1    | 60                   | 60                    | 60                  |
|         | V-3    |                      |                       |                     |
|         | Kr-5   |                      |                       |                     |
Types of construction were also considered. During the research, the data were divided into two clusters (Table 3).

**Table 3. Types of construction clusters**

| Cluster | Symbol | Roof         | Floor                    | Wall         |
|---------|--------|--------------|--------------------------|--------------|
| 1       | P-2    | Iron roof    | Timber floor             | Brick wall   |
|         | M-2    |              |                          |              |
|         | M-3    |              |                          |              |
| 2       | N-4    | Roll roofing | Cast reinforced concrete slab | Brick wall |
|         | N-5    |              |                          |              |
|         | N-3    |              |                          |              |
|         | Kir-2  |              |                          |              |
|         | T-2    |              |                          |              |
|         | T-3    |              |                          |              |
|         | Kir-4  |              |                          |              |
|         | T-1    |              |                          |              |
|         | P-3    |              |                          |              |
|         | K-4    |              |                          |              |
|         | Kr-3   |              |                          |              |
|         | F-2    |              |                          |              |
|         | N-1    |              |                          |              |
|         | N-2    |              |                          |              |
|         | Kr-1   |              |                          |              |
|         | K-1    |              |                          |              |
|         | V-5    |              |                          |              |
|         | A-5    |              |                          |              |
|         | P-1    |              |                          |              |
|         | K-3    |              |                          |              |
|         | F-5    |              |                          |              |
|         | M-1    |              |                          |              |
|         | V-1    |              |                          |              |
|         | V-3    |              |                          |              |
|         | Kr-5   |              |                          |              |

4 Discussion

The program has divided the objects into 7 clusters depending on the indicators of physical deterioration of structural elements of buildings. With the increase of the cluster number, the indicators of physical wear decrease. Characteristics of physical wear clusters received in the program Deductor can be reduced thus it will reduce their number. Recommendations can be made for follow-up actions based on the results (Table 4).

**Table 4. Recommendations**

| Cluster | Symbol | Technical condition | Recommendations                                                                 |
|---------|--------|---------------------|--------------------------------------------------------------------------------|
| 4       | Kr-1   | Satisfactory        | Requires minor repairs with elimination of local damage without strengthening of the constructions |
|         | N-1    |                     |                                                                                  |
|         | N-2    |                     |                                                                                  |
|         | N-4    |                     |                                                                                  |
|         | N-5    |                     |                                                                                  |
|         | N-3    |                     |                                                                                  |
|         | Kir-2  |                     |                                                                                  |
|         | T-2    |                     |                                                                                  |
|         | T-3    |                     |                                                                                  |
| 3       | Kir-4  | Unsatisfactory      | Major repairs with strengthening and restoring the capacity are required to ensure normal operation |
|         | T-1    |                     |                                                                                  |
|         | P-3    |                     |                                                                                  |
| 2       | K-4    | Pre-emergency       | The buildings in this cluster belong to the objects of cultural heritage. Immediate safety measures are required (unloading of structures, temporary support, etc.). Operation of the building |
Two clusters were identified according to the design characteristics. Then the thermotechnical calculation of the wall and selection of insulation were made for the reconstruction. Composition of the existing outer wall is shown in Table 5.

**Table 5. Composition of the existing outer wall**

| №  | Layer          | Layer name   | Specific gravity t, kg/m³ | Thicknesses δ, m | Thermal conduction λ, W/(m·°C) | δ/λ, m²·°C/W |
|----|----------------|--------------|---------------------------|------------------|-------------------------------|--------------|
| 1  | Load-bearing   | Brick wall   | 1400                      | 0.51             | 0.64                          | 0.797        |
|    | TOTALS:       |              |                           |                  |                               |              |

Heating degree-day:

\[ HDD = (t_{int} - t_{ext}) \cdot z_{a} \]  \hspace{1cm} (1)

According to SP 50.133330.2012 «Building heat insulation» \( HDD = 4749.9 \) °C·day

Normalized heat transfer resistance of the outer wall:

\[ R_n = \alpha \cdot HDD + \beta \] \hspace{1cm} (2)

where \( \alpha, \beta \) - design factors, according to SP 50.133330.2012 «Building heat insulation»:

\( \alpha = 0.00035; \beta = 1.4. \)

\( R_n = 0.00035 \cdot 4749.9 + 1.4 = 3.063 \) m²·°C/W

Design heat transfer resistance of the outer wall:

\[ R = 1 / \alpha_{int} + \Sigma (\delta/\lambda) + 1 / \alpha_{ext} \] \hspace{1cm} (3)

\( R = 0.115 + 0.797 + 0.044 = 0.956 \) m²·°C/W

Considering the factor of homogeneity of the solid brick wall made of hollow bricks we get:

\( R = 0.956 \cdot 0.97 = 0.927 \) m²·°C/W

Conclusion:

\( R = 0.927 \) m²·°C/W < \( R_n = 3.063 \) m²·°C/W
The calculation value of the surface heat exchange resistance is significantly lower than normalized value. Consequently, the existing design of the outer wall does not meet modern requirements for thermal protection of buildings.

Composition of the outer wall. Selection of the insulation is shown in Table 6.

**Table 6.** Composition of the outer wall. Selection of insulation material

| №  | Layer   | Layer name             | Specific gravity t, kg/m³ | Thickness δ, m | Thermal conduction λ, W/(m·°C) | δ/λ m²·°С/W |
|----|---------|------------------------|---------------------------|----------------|-------------------------------|-------------|
| 1  | Load-bearing | Brick wall            | 1400                      | 0.51           | 0.64                          | 0.797       |
| 2  | Insulation | Mineral wool           | 90                        | 0.10           | 0.035                         | 2.857       |
|    | TOTALS: |                        |                           | 0.61           |                               | 3.654       |

Normalized heat transfer resistance of the outer wall:

\[ R_n = \alpha \cdot HDD + \beta = 3.063 \text{ m}^2\cdot\text{°C/W} \]

where \( \alpha, \beta \) - design factors: \( \alpha = 0.00035; \beta = 1.4 \).

Design heat transfer resistance of the outer wall:

\[ R = \frac{1}{\alpha_{int}} + \sum (\frac{\delta}{\lambda}) + \frac{1}{\alpha_{ext}} = 0.115 + 3.654 + 0.044 = 3.812 \text{ m}^2\cdot\text{°C/W} \]

Considering the factor of homogeneity we get:

\[ R = 3.812 \cdot 0.97 = 3.698 \text{ m}^2\cdot\text{°C/W} \]

Conclusion:

\[ R = 3.698 \text{ m}^2\cdot\text{°C/W} > R_n = 3.063 \text{ m}^2\cdot\text{°C/W} \]

The calculation value of the surface heat exchange resistance is significantly above normalized value. Consequently, the existing design of the outer meets modern requirements for thermal protection of buildings and can be used in the buildings reconstruction.

Composition of the outer wall is shown in Table 7.

**Table 7.** Composition of the outer wall. Selection of insulation material

| №  | Layer   | Layer name             | Specific gravity t, kg/m³ | Thickness δ, m | Thermal conduction λ, W/(m·°C) | δ/λ m²·°С/W |
|----|---------|------------------------|---------------------------|----------------|-------------------------------|-------------|
| 1  | Load-bearing | Brick wall            | 1400                      | 0.51           | 0.64                          | 0.797       |
| 2  | Insulation | Aerogel based thermal insulation | 150                      | 0.04           | 0.014                         | 2.857       |
|    | TOTALS: |                        |                           | 0.55           |                               | 3.654       |

Normalized heat transfer resistance of the outer wall:

\[ R_n = \alpha \cdot HDD + \beta = 3.063 \text{ m}^2\cdot\text{°C/W} \]

where \( \alpha, \beta \) - design factors, according to SP 50.133330.2012 « Building heat insulation»: \( \alpha = 0.00035; \beta = 1.4 \).
Design heat transfer resistance of the outer wall:

\[ R = \frac{1}{\alpha_{\text{int}}} + \sum \left( \frac{\delta}{\lambda} \right) + \frac{1}{\alpha_{\text{ext}}} = 0.115 + 3.654 + 0.044 = 3.812 \, \text{m}^2 \cdot \text{°C}/\text{W} \]

Considering the factor of homogeneity:

\[ R = 3.812 \cdot 0.97 = 3.698 \, \text{m}^2 \cdot \text{°C}/\text{W} \]

Conclusion:

\[ R = 3.698 \, \text{m}^2 \cdot \text{°C}/\text{W} > R_n = 3.063 \, \text{m}^2 \cdot \text{°C}/\text{W} \]

The calculation value of the surface heat exchange resistance is above normalized value. It is equal to the results obtained for mineral wool boards 100 mm thick. Consequently, the existing design of the outer meets modern requirements for thermal protection of buildings and can be used in the buildings reconstruction.

4 Conclusion

The research identified objects of the gray belt - industrial areas surrounding the historical district of St. Petersburg, Russia, defined building dilapidation for each object; were created clusters according to the characteristics of the physical wear and types of construction.

Recommendations were given for the reconstruction considering the parameter of physical wear, selected insulation for external load-bearing walls that meets the requirements for energy efficiency of buildings.

The method of object clustering is based on the fact that it is possible to consider typical methods when making a decision on reconstruction. Standard solutions will allow to make the reconstruction process with minimal costs.

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