Multi-criteria assessment of pitched roof reconstruction technologies

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Abstract. The paper examines the technologies of reconstruction of sloping-pitched roofs, their application and efficiency. The analysis consist of the main characteristics of pitched roofs types, causes of their damages. The work also analyzes roof defects, the main causes of these defects. There are described ways how to improve performance of roofs. Three different reconstruction technologies are distinguished, which are compared between each other using multi-criteria evaluation methods ARAS (additive ratio assessment) and COPRAS (Complex Proportional Assessment). After performing a multi-criteria assessment, we found that the use of polyurethane foam is the best choice for roof reconstruction work.

Keywords: reconstruction, pitched roof, multi-criteria assment, COPRAS, ARAS.

Introduction

We could say that roof is the main element of each building which is responsible for the performance of the whole building. In order to assess the condition of buildings, it is usually necessary to evaluate the individual elements and their components, but it can be stated that the state of all these individual elements depends mainly on how much the building is resistant to external factors – usually precipitation. We can say that the overall condition of a building depends mostly on one structure – roof. Various ways of constructing and shaping roofs have been widespread since ancient times, but even since then most often, residential houses are found with roofs of wooden structures. In other cases steel structures are found. When designing a roof, the focus is usually on the region, also on average temperature and precipitation. These factors often determine the shape of the roof itself. The high snowfall in the regions determines that the houses under construction have pitched-pyramid roofs that withstand high snow loads and prevent the accumulation of large amounts of snow due to the higher slope. Each roof is unique, it has its own strengths and weaknesses, usually the shape determines the roof damage and defects. Removing the defects it should be taken into account that the roof structure itself has an influence to the materials used, as same as to the repair technology. Roof reconstruction technology and its quality determine extension of roof usage time.

Most common damage types of pitched roofs. The roof is one of the most exposed building element to the environment, so most often the repair or reconstruction of the building is due to a poor roof. The main problems of poor installation, defects and damage are almost found in all roof structures. Even roofs in tropical climates have almost the same type of damage as here in more Nordic regions (Carretero-Ayuso, Moreno-Cansado, & de Brito, 2017). With reference to Gullbrekken, Kvande, Jelle, and Time (2016) and Carretero-Ayuso et al. (2017) and their research material, the main roof defects are presented in Table 1.

No matter what the roof is, the factors on the roof can work the same, depending on the climatic conditions (see Table 2). Lars Gullbrekken in his analysis of poor roof defects has highlighted the factors that have the greatest impact on all possible roofs (Gullbrekken et al., 2016). According to him, the critical factor is snow, which accumulates on the roofs, fluctuating in temperature, it melts and freezes again and expands. As a result, wooden structures are expanded due to the moisture content, and when the weather is warm, it absorbs even more moisture. Other roofing materials have started to roll down because of such humidity circulation. It should also be taken into account if the roof is not heated, snow does not provide ventilation, and the humidity is closed inside.

Table 1. Main roof defects

Defect	Defect object	The main cause	Frequency (1–100%)
Moisture	Thermal insulation layer	Poor ventilation	31.5
Accumulation of condensate	Thermal insulation layer, timber elements	Incorrectly installed diffuse layer	21.0
Structural cracks	Bearing timber constructions	Material aging, moisture	11.3
Mold	Thermal insulation layer, timber	Lack of ventilation	9.5
Single element damage	–	Aging	9.3
Coating damage	Roof cover layer	Sunlight, ice dams	8.1
Others	–	–	9.3

Table 2. The main factors which cause defects in single elements

Factor	Frequency (1–100%)
Moisture	51.6
Poor installation	21.5
Aging of materials	11.5
Poor maintenance	5.1
Incorrect ventilation	5.0
Others	5.3

Most common roof types found in Europe

Roof types and their structures

There are several hundred types of roofs found these days. But following types of roofs are most common (Roofpedia, 2018; Designing Buildings Wiki, 2018):

- Shed roof, a roof that is usually used the most if the roof is not in use, is covered by a large span, and a small slope is formed.
- Front gabled roofs, a traditional roof that is used to partially install an attic floor. Main characteristic is high slope.
- Mansard type (attic), a broken roof that is chosen to maximize the use of attic floors. The disadvantage of this type is banging.
- Pyramid, the roof of intersecting structures that are most common in building new homes. These roofs usually have special height attributes. This type of roof is most common in Germany.
- Gambrel roof, this is the roof where the attic is partially installed, this type of roof is most commonly found in Scandinavia.
- Multi-ply roofs, which are combined with multiple roofs. These roofs are usually made of combined wood and steel.
- The main structures and elements of above mentioned roofs are (MYROOF, 2017):
- Rafters are the main roof-facing structure on which load is distributed. The rafters are solid up to 6 m, positioned at intervals of 0.8–1.2 m.
- Shelters – so-called rafters longer than 6 m. More often, the term shelter is found when there are broken roofs (attic).
- Masonry is a structure that connects eaves and masonry. In most cases, the masonry is derived from the perimeter (or masonry) of the monolithic ring and is anchored to the supporting structure. The main function is to distribute the load on the rafters.
- The strut, it is a vertical structure supported by a crank that prevents movement and creep.
- String/lower strap is a horizontal structure that pulls the eave to prevent them from moving horizontally.
- Rake board /beam – structure joining the top of rafters. The roof is additionally equipped for installation.

Most common roof structure types in Lithuania

- Typical, this is a method of disassembling rafters, where the main load is divided into eave – fracture. This disintegration is most often found with low, exploited, roofed roofs (Figure 1).

Figure 1. A typical schematic diagram of rafters

- String restrain structures, which is usually found in pyramidal roofs, which have a specific height. The load is distributed on the rafters, which are stretched by horizontal and vertical strings. This type of roofing is widespread in Germany, and in Lithuania it is possible to see these roofs in Klaipeda region (Figure 2).

Figure 2. Schematic of the strapping of string rafters

- Strut-web constructions, it is a method of disassembling rafters where the entire load of the roof is divided into clamps retracted from the roof, which are angled or vertical. This type of roofing is spread in Scandinavia, where roofs withstand heavy snow loads. Often these roofs are made for sod / turf roofs (they are similar to green roofs). These roofs are considered traditional Scandinavian roofs. They many air gaps, which act as a thermo-insulating layer. Due to the green layer, the roof must withstand high loads and have excellent waterproofing (Figure 3).

Figure 3. Schematic of the strut-web rafters

Physical and moral roof depreciation

After evaluating the damage to the roof, further factors can be taken to extend the roof exploitation. According to what kind of shape are the bearing constructions and separate elements, the question is raised it is worth repairing-reconstructing, usually in case of more than 50% physical wear and tear (see Table 3), refurbishment work is not done because it is cheaper to demolish and rebuild a new roof (Hansson, 2017). However, this is not valid for heritage buildings, but works in these buildings are even reconstructed even if the whole roof is in an emergency status. With reference to Hansson (2017) and Ahluwalia and Hegazy (2010), we can classify roof physical depreciation by quantity of defects (Table 3).

Table 3. Physical depreciation classification

Condition (%)	Symptoms
Good (0–20)	No major damage or deformation, slight water damage, condensate, loss of strength, no cracks in wood
Satisfactory (21–40)	Damage to small supporting structures, no noticeable deformations, water damage, condensate
Unsatisfactory (41–60)	Major structural damage, deformation, excess moisture, mold, condensation, cracks and gaps between individual elements. Repair required
Bad (61–80)	High structural damage and deformation poses a safety hazard, high humidity. Reconstruction is required
Emergency (81–100)	Obvious violations, mismatches in the norms causing danger. Full reconstruction is needed

Performing reconstruction or repairs does not necessarily depend on physical wear and tear. The main causes of moral deprivation are technical progress and the growth of various societal needs. Usually roof repairs are done to increase the energy efficiency of buildings.

The most common old roof reconstruction used is reinforcing the roof support by installing additional supporting structures and a new thermal insulation layer. If the old roof rafters were arranged every 1.2 m from each other, then it is usually enough to put one new raft in the spaces, so-called “strings” between the rafters and the roof structure will be ready to withstand all loads (Gurkšnys & Kavaliauskas, 2011). Such a construction can be used when the raft spacing is up to 4.75 m at a 45–60 degree roof slope. The most important step in every roof reconstruction is to install a suitable diffusive film, which will allow the roof to evaporate all the moisture and protect the wooden structure from rotting. After these main steps, roof insulation and finishing can be done (Bakri & Mydim, 2014)

Roof insulation technologies

The pitched roof structure is special in that it has more intersection points than a flat. Every intersection, angle, junction is a threat to a cold bridge that increases energy loss. Depending on the quality of the project and installation work, the heat loss through cold bridges is between 10 and 30% of the total heat loss (Ahluwalia & Hegazy, 2010). One of the major problems with roof insulation is when thermal insulation is placed between the rafters and the integrity of the material is not maintained, so the rafters become a large thermal bridge. In such cases, there are more problems: the temperature of the inner surfaces decreases, the heat loss increases, and in the worst case, large amounts of moisture can build up on the structures. In many cases, however, the shell cannot be avoided because the roof rafters do not only serve as a roof baring function, but are also necessary as a support for fiber insulation. As the required amount of wool grows, the height of the rafters increases, which determines not only the cost of the structure, but also the weight of the latter (Kucera, Hienonen, Suhajda, & Illikainen, 2017).

The main aspect that needs to be taken into account when rebuilding roofs is the load that will emerge from the new elements. We can say that old bearing structures cannot be insulated with the necessary insulation layer, and in order to get the necessary energy efficiency, the old structures should be significantly strengthened. This leads to the fact that reconstruction is usually uneconomical and technologically difficult, that it is cheaper to install a new roof construction (ROCKWOOL, 2018).

The most common methods-technologies of thermal roof insulation:

1. **Thermal insulation using wool batting.** This is the most widely used building material for insulation works. These are materials that are easy to work with, and do not require additional equipment or tools. Using these materials makes it difficult to work with cracks that are difficult to clog. Therefore, cracks are often left that become cold bridges. Wool is characterized by the ability to get wet and lose its thermal properties. Using the materials, the most important step is the installation of diffusive layer that prevents the accumulation of excess water (PAROC, 2019).
2. **Thermal insulation using sprayed polyurethane foam.** This is a fairly new material, especially for roof repairs. The main advantage of this material is that the foam fills all the bumps and gaps that are not covered with other materials, eliminating almost all the cold bridges. The foam itself, not like cotton wool, is not afraid of excess moisture, so the diffusive layer is not so important for the insulation of the roof with the spraying materials. Polyurethane foam is very light, it bonds with all insulated surfaces and created an especially “warm” layer with great insulation properties (RUKKI, 2017).
3. **Thermal insulation using polyurethane plates.** This type of insulation is usually found when installing sandwich panels on walls, but more and more often this method is found in roof reconstruction works with modified panels. These panels are usually mounted not between the rafters, but on them, this solution eliminates almost all cold bridges. However, there are other problems, such as the installation of a diffuse, waterproofing layer on the sheets, the installation of the coating. All this requires complex design and installation of additional materials (RUKKI, 2017).

Multi-criteria assessment of roof reconstruction – repair technologies

In order to evaluate what technology is best in renovating a roof, several roof types should be considered. This is because, depending on the type of roof, different materials, construction technology has its own specificity, influenced by the overall result. Therefore, each technology will be evaluated on the 3 most widely used roof structures, described in Section 2.2. But multi-criteria evaluation will be done on 2 different roof types, because the stringed and strutted roofs are almost the same. There are many multiple criteria decision making (MCDM) methods over the world (Zavadskas & Turskis, 2011). In this study we are going to employ two of them developed by Vilnius Gediminas Technical University (VGTU) scientists.

Additive Ratio assessment (ARAS) method

Based on Zavadskas and Turskis (2010), the following thermal insulation technologies are compared between each other, the following results are (Table 4):

Table 4. Decision-making matrix. Typical roof construction

Criteria Technology	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN
Q_i	0.1	0.3	0.1	0.3	0.2
Thermal insulation using wool batting	6	74	16	86	5
Thermal insulation using sprayed polyurethane foam	3	90	19.5	97	3
Thermal insulation using polyurethane plates	8	96	14.5	82	8

The next step is to transform the decision matrix so that the all criterias are maximized (Table 5):

Table 5. Transformed decision-making matrix. Typical roof construction

Criteria Technology	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN
Q_i	0.1	0.3	0.1	0.3	0.2
Thermal insulation using wool batting	0.167	0.014	0.063	86	0.200
Thermal insulation using sprayed polyurethane foam	0.333	0.011	0.051	97	0.333
Thermal insulation using polyurethane plates	0.125	0.010	0.069	82	0.125

After transforming the matrix to maximize all its criteria (Table 5), we will normalize the matrix (Table 6):

Table 6. Normalized decision-making matrix. Typical roof construction

Criteria Technology	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum ma- terial weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN
Q_i	0.1	0.3	0.1	0.3	0.2
Thermal insulation using wool batting	0.267	0.400	0.344	0.325	0.304
Thermal insulation using sprayed polyurethane foam	0.533	0.314	0.279	0.366	0.506
Thermal insulation using polyurethane plates	0.200	0.286	0.377	0.309	0.190

Composing a weighted matrix, determining performance indexes R_j and efficiency degrees N_j (Table 7):

Table 7. Weighted decision-making matrix. Typical roof construction

Technology \ Criteria	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)	Performance Index R_j	Degree of efficiency N_j (%)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN		
Q_i	0.1	0.3	0.1	0.3	0.2		
Thermal insulation using wool batting	0.027	0.120	0.034	0.098	0.061	0.340	88
Thermal insulation using sprayed polyurethane foam	0.053	0.094	0.028	0.110	0.101	0.386	100
Thermal insulation using polyurethane plates	0.020	0.086	0.038	0.0927	0.038	0.275	71

The same method is done with the other roof type (Table 8 and Table 9):

Table 8. Decision-making matrix. Stringed and strutted roofs constructions

Technology \ Criteria	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN
Q_i	0.1	0.3	0.1	0.3	0.2
Thermal insulation using wool batting	8	56	19.7	61	8
Thermal insulation using sprayed polyurethane foam	3	90	22.8	74	3
Thermal insulation using polyurethane plates	8	96	14.5	82	9

Table 9. Weighted decision-making matrix. Stringed and strutted roofs constructions

Technology \ Criteria	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)	Performance Index R_j	Degree of efficiency N_j (%)
Minimize / maximize	MIN	MIN	MIN	MAX	MIN		
Q_i	0.1	0.3	0.1	0.3	0.2		
Thermal insulation using wool batting	0.021	0.139	0.031	0.084	0.044	0.319	82
Thermal insulation using sprayed polyurethane foam	0.057	0.085	0.027	0.102	0.117	0.388	100
Thermal insulation using polyurethane plates	0.021	0.077	0.042	0.113	0.039	0.292	75

Complex Proportional Assessment (COPRAS) method

Based on Zavadskas, Kaklauskas, and Sarka (1994) the same calculations are done with the other method Complex Proportional Assessment (COPRAS) the results are following (see Tables 10–11):

Table 10. Decision-making matrix. Typical roof construction

Criteria \ Technology	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)	S _{+j}	S _{-j}	Q _j	N _j
Minimize / maximize	MIN	MIN	MIN	MAX	MIN				
Q _i	0.1	0.3	0.1	0.3	0.2				
Thermal insulation using wool batting	0.035	0.085	0.032	0.097	0.063	0.097	0.215	0.344	91
Thermal insulation using sprayed polyurethane foam	0.018	0.104	0.039	0.110	0.037	0.110	0.198	0.378	100
Thermal insulation using polyurethane plates	0.047	0.111	0.029	0.093	0.100	0.093	0.287	0.277	73

The same calculations are provided to the other roof type.

Table 11. Decision-making matrix. Stringed and struttred roofs constructions

Criteria \ Technology	Complexity (Score 1–10)	Elimination of cold bridges (1–100%)	Minimum material weight (kg/m ³)	Density (1–100%)	Need for additional structures and elements (Score 1–10)	S _{+j}	S _{-j}	Q _j	N _j
Minimize / maximize	MIN	MIN	MIN	MAX	MIN				
Q _i	0.1	0.3	0.1	0.3	0.2				
Thermal insulation using wool batting	0.042	0.069	0.035	0.084	0.080	0.084	0.226	0.320	86
Thermal insulation using sprayed polyurethane foam	0.016	0.112	0.040	0.103	0.030	0.103	0.198	0.372	100
Thermal insulation using polyurethane plates	0.042	0.119	0.025	0.113	0.090	0.113	0.276	0.307	83

Conclusions

After performing a multi-criteria assessment, we found that the use of polyurethane foam is best suited for roof reconstruction work. This work technology is particularly well suited for effective heat resistance, as there are cracks filled in the rafters that are the main cold bridges. When evaluating reconstruction in general, the most important step is to evaluate the complexity of the roof itself and the condition, as not all reconstruction works will be useful and effective. At present, not all technologies are fully worked out because each building has its own specificity, so it could be argued that the technique used during one reconstruction can be ineffective when applied massively.

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