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MULTI-CRITERIA EFFICIENCY EVALUATION OF BIO-BASED WALL THERMAL INSULATION MATERIALS FOR ZERO-EMISSION PUBLIC BUILDINGS USING THE ARAS METHOD

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Abstract. This research evaluates bio-based wall thermal insulation materials for zero-emission public buildings by applying the additive ratio assessment (ARAS) method, which provides a systematic framework for ranking alternatives based on multiple criteria, thereby supporting sustainable building design decisions. The assessment of four bio-based thermal insulation materials (compressed straw bale; hemp fiber; flax (linen) fiber and wood fiber insulation) was conducted using six selected criteria: average material price in 2025-3Q, €/m²; average insulation material thermal conductivity, W/m·K; reference service life, years; global warming potential (GWP-fossil in A1-A3 stages), kg CO2eq/ m²; the fire resistance class of the material, points; required insulation thickness at a wall's U-value of 0.12, m. The results of the empirical research demonstrate that among the evaluated wall bio-based insulation alternatives, compressed straw bale stands out as the most effective material for zero-emission public buildings. This insulation material attained the highest relative performance index of 0.85, reflecting its superior ranking within the ARAS evaluation framework. Among the four assessed alternatives, the insulation materials based on hemp fiber and flax (linen) fiber exhibited the lowest degree of utility, scoring 0.70 and 0.66 points respectively. The performance gap between the optimal and least favorable alternatives was found to be 22.43 percent.

Keywords: external wall; bio-based thermal insulation materials; zero-emission public building; ARAS method

INTRODUCTION

Directive (EU) 2024/1275 formally introduces the "zero-emission" building concept, setting a new benchmark for sustainable construction within the European Union. However, under the current Lithuanian technical construction regulation (STR 2.01.02:2016), buildings that would fall under this category are still regulated according to A++ class energy performance requirements (Aviža, 2024). It is anticipated that these national standards will be reviewed and potentially updated in the near future to align fully with the emerging "zero-emission" criteria prescribed by the Directive, reflecting evolving environmental policies and construction best practices.

The scientific literature encompasses a wide array of analyses regarding bio-based thermal insulation materials (Aybar et al. 2025; Bąk 2025; Bourbia et al. 2023 and others). Even though data on several aspects of bio-based thermal insulation materials are available, comprehensive information on their efficiency performance evaluation across multiple criteria for public buildings is lacking. Consequently, this study provides a detailed examination of typical bio-based thermal insulation materials used in exterior walls of zero-emission (A++ class) public buildings. Based on the results of the ARAS empirical analysis, the most efficient bio-based thermal insulation material is identified.

The purpose of this paper is: to evaluate the multi-criteria efficiency of bio-based wall thermal insulation materials for zero-emission public buildings in Lithuania using the ARAS method.

This study is focused on achieving the following goals:

1. to analyze the algorithmic framework of the ARAS method in multi-criteria decision-making.
2. to design a research model grounded in a typical exterior wall detail for a zero-emission public building in Lithuania (apply the presently valid A++ class standards, with an understanding that updates may occur in the near future).
3. to perform a multi-criteria evaluation of the effectiveness of four different external wall bio-based thermal insulation materials by applying six criteria.

Research methods: technical and scientific literature review; empirical data analysis; ARAS-based evaluation.

THE ARAS METHOD

The additive ratio assessment (ARAS) method, formulated by Zavadskas and Turskis in 2010, offers a comprehensive multi-criteria decision-making framework with a well-structured step-by-step algorithm involving the decision matrix formulation, normalization, the selection of a reference or optimal alternative, the calculation of weighted sums, and the assessment of the utility degree, demonstrated through an applied case example (Zavadskas & Turskis 2010). This method effectively manages benefit and cost criteria, providing results that are both transparent and easy to interpret (Gunawan et al. 2025). Its simplicity and precision make ARAS a popular choice for applications including site selection, building option selection, performance evaluation, and others (Table 1).

Table 1

Examples of ARAS Method Applications

Author (year of publication)	Method used	Application Focus
Özçil et al. (2025)	IRPA-(ARAS-MCDM)	Integrative Reference Point Approach
Yücenur et al. (2024)	ENTROPY- ARAS	Site selection of a hydroponic geothermal greenhouse
Mishra et al. (2023)	IF-MEREC-SWARA-ARAS	Selecting the optimal sustainable industrial building option
Goswami et al. (2022)	COPRAS-ARAS	Electrical discharge machining parameters in a green production environment

The algorithm for ranking different alternatives using the ARAS method is as follows (Kumari & Acherjee 2025):

1. Construct the Decision Matrix.
2. Determine the Optimal Performance Ratings.
3. Calculate the Normalized Decision Matrix.
4. Calculate the Weighted Normalized Decision Matrix.
5. Calculate the Overall Performance Index.
6. Calculate the Degree of Utility.

By performing a 6-step multi-criteria analysis, it is possible to establish a priority order and calculate the most effective alternative.

THE RESEARCH MODEL

The research model was developed based on a typical external wall detail — rendered facade (ETICs) — of a zero-emission public building meeting A++ class standards in Lithuania. The tested layer is Layer number 1 (Figure 2).

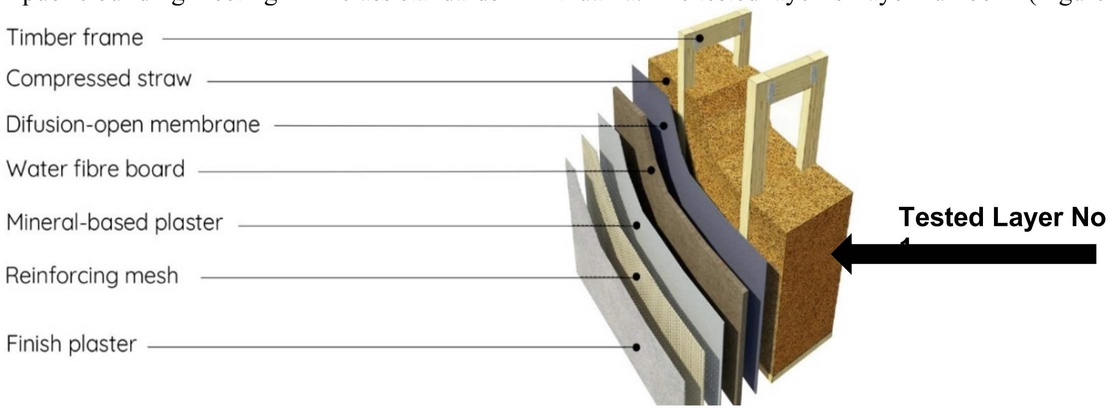

Figure 2. **The research model (for the explanation of layers, see Table 2). Source: modulina.eu**

In accordance with the Technical Regulations of Construction STR 2.01.02:2016, the required heat transfer coefficient for an A++ class public wall, U=0.12 W/m²K and the thickness of bio-based thermal insulation materials were calculated.

Table 2

The explanation of the wall layers

No	Name of the layer	Thickness, mm
1	**Bio-Based Thermal Insulation Materials**	370÷540
	Timber frame (10 %)	
2	Diffusion-open membrane	
3	Water fiber board	
4	Mineral-based plaster	
5	Reinforcing mesh+Finish plaster	

The investigation focused on assessing four types of bio-based thermal insulation materials: compressed straw bale; hemp fiber; flax (linen) fiber and wood fiber insulation.

For the multi-criteria assessment of these four bio-based thermal insulation materials, the ARAS (Additive Ratio Assessment) method was applied considering six evaluation criteria.

THE RESEARCH METHODOLOGY AND OUTCOMES

In the initial phase of the ARAS performance evaluation, a primary decision matrix (Table 3) was constructed to assess four distinct bio-based thermal insulation wall materials — compressed straw bale (M1), hemp fiber (M2), flax (linen) fiber (M3), and wood fiber (M4) — using six criteria derived from technical specifications, Environmental Product Declarations (EPD) and the product data platform (2050 Materials): the average material price in 2025-3Q (C1), €/m²; the average insulation thermal conductivity (C2), W/m·K; the reference service life (C3), years; the global warming potential (GWP-fossil in A1-A3 stages), (C4), kg CO_2eq/ m²; the fire resistance class of material (C5), points (for Euroclass "D"- 3 points; for "E"- 2 points); the insulation thickness at a wall's U-value of 0.12 (C6), m (for A++ class public building). In the next stage of the evaluation, the optimal alternative is identified (Table 3). Equal significance is attributed to all criteria, each weighted at 0.167.

Table 3

Decision-Making Matrix and Optimal Performance

Material alternatives/ Significances/ Optimization	**Criteria**					
	The average material price in 2025-3Q (C1), €/m²	***The average insulation thermal conductivity (C2), W/m·K***	***The reference service life (C3), years***	***The global warming potential (GWP-fossil in A1-A3), (C4), kg CO_2eq/m^2***	***The fire resistance class of the material, (C5), points***	***The insulation thickness at a wall's U-value of 0.12 (C6), m***
Compressed straw bale (M1)	27.00	0.059	75.0	9.98	2.0	0.54
Hemp fiber (M2)	66.40	0.040	60.0	25.49	3.0	0.40
Flax (linen) fiber (M3)	101.79	0.038	75.0	24.85	2.0	0.39
Wood fiber (M4)	40.29	0.036	50.0	14.63	2.0	0.37
Significance	0.167	0.167	0.167	0.167	0.167	0.167
Optimization	MIN	MIN	MAX	MIN	MAX	MIN
Optimal Alternative (A0)	27.00	0.036	75.0	9.98	3.0	0.37

The primary decision-making matrix was normalized in the subsequent step (Table 4).

Table 4

Normalized Decision Matrix

Material alternatives	**Criteria**					
	C1	***C2***	***C3***	***C4***	***C5***	***C6***
A0 - optimal	0,4270	0,2892	0,2885	0,4039	0,3333	0,2810
Compressed straw bale (M1)	0,4270	0,1765	0,2885	0,4039	0,2222	0,1925
Hemp fiber (M2)	0,1736	0,2603	0,2308	0,1582	0,3333	0,2599
Flax (linen) fiber (M3)	0,1133	0,2740	0,2885	0,1622	0,2222	0,2666
Wood fiber (M4)	0,2861	0,2892	0,1923	0,2757	0,2222	0,2810

The weighted normalized decision matrix was presented in the following step (Table 5).

Table 5

Weighted Normalized Decision Matrix

Material alternatives	**Criteria**					
	C1	***C2***	***C3***	***C4***	***C5***	***C6***
A0 - optimal	0,0712	0,0482	0,0481	0,0673	0,0556	0,0468
Compressed straw bale (M1)	0,0712	0,0294	0,0481	0,0673	0,0370	0,0321
Hemp fiber (M2)	0,0289	0,0434	0,0385	0,0264	0,0556	0,0433
Flax (linen) fiber (M3)	0,0189	0,0457	0,0481	0,0270	0,0370	0,0444
Wood fiber (M4)	0,0477	0,0482	0,0321	0,0459	0,0370	0,0468

Final calculations included the determination of the Overall Performance Index (Si), the Degree of Utility, and the Rank, as shown in Table 6.

Table 6

Ranking alternatives

Material alternatives	**Overall Performance Index (Si)**	**Degree of Utility** (Ki)	**Rank**
A0 - optimal	0,3371	1,0000	Reference
Compressed straw bale (M1)	0,2851	0,8456	1
Hemp fiber (M2)	0,2360	0,7001	3
Flax (linen) fiber (M3)	0,2211	0,6559	4
Wood fiber (M4)	0,2578	0,7645	2

Once the multi-criteria ARAS evaluation was finalized, the efficiency scores were computed for each bio-based thermal insulation material (Figure 2).

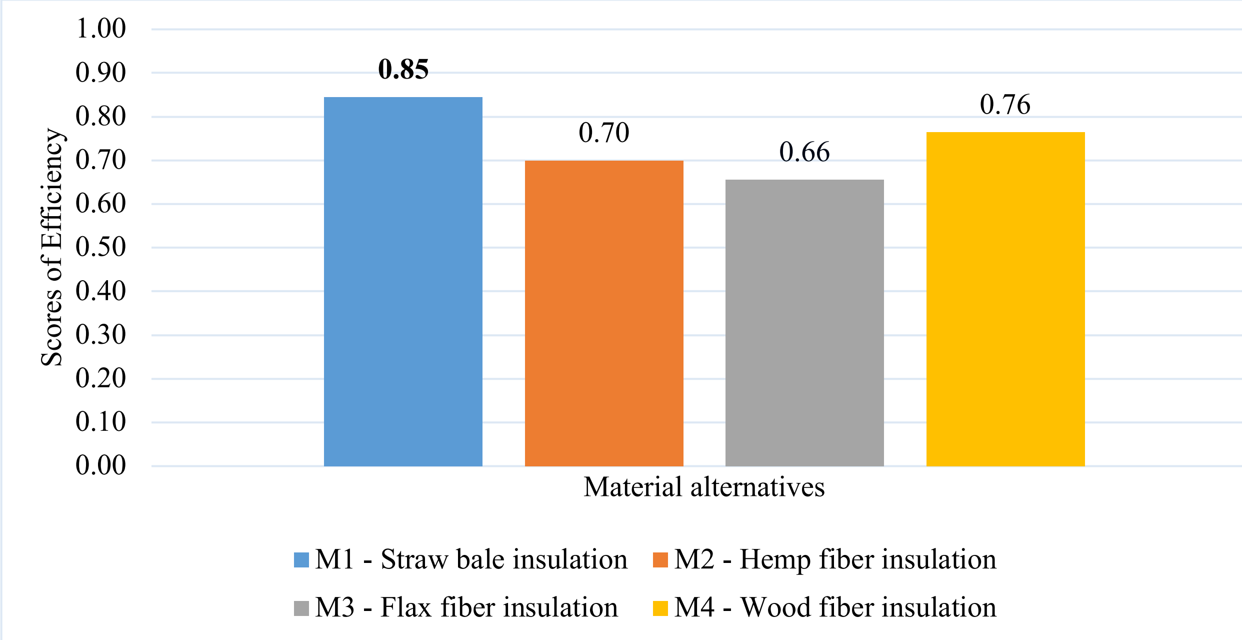

Figure 2. **The assessment of the efficiency of bio-based thermal insulation materials**

Empirical results demonstrate that, among bio-based thermal insulation materials for a zero-emission public building, compressed straw bale insulation is the most effective external wall option, while flax (linen) fiber insulation's relative score of 0.66 represents the least effective (Figure 2).

CONCLUSIONS

1. By the ARAS method, it was determined that the most effective wall bio-based thermal insulation material for a zero-emission public buildings (taking into account four insulation alternatives and six evaluation indicators) is compressed straw bale insulation. This alternative scored the highest number of efficiency points (0.85).
2. The second place in the assessment goes to wood fiber insulation. It scored 0.76 relative efficiency points.
3. The least effective options (from the four tested alternatives) are hemp fiber (0.70 points) and flax (linen) fiber insulation (0.66 points). The variance between the optimal and least favorable alternatives equals 22.43 percent.

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