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MULTICRITERIA ANALYSIS OF GLOBAL WARMING POTENTIAL IMPACT ON THERMAL INSULATION SELECTION: SCENARIOS AND SENSITIVITY ASSESSMENT

Slobodan Peulić[a], Goran Janjić[b], Darija Gajić[a], Saša Čvoro[a]

[a]*University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, University City, Bulevar vojvode Petra Bojovića, 78000 Banja Luka, Republic of Srpska, Bosnia and Herzegovina*
[b]*University of Banja Luka, Faculty of Mechanical Engineering, University City, Bulevar vojvode Stepe Stepanovića 71, 78000 Banja Luka, Republic of Srpska, Bosnia and Herzegovina*

Abstract *By selecting the appropriate thermal insulation materials, it is possible to reduce CO_2 emissions in the construction sector. This study analyzes the environmental and economic aspects of insulation materials through the Global Warming Potential (GWP) and climate change costs. The results show that renewable materials, such as cellulose and wood fibers, have a negative GWP, while glass wool, mineral wool, and EPS generate significant CO_2 emissions. Using multi-criteria analysis in the Super Decisions software, the justification for choosing between renewable and non-renewable materials is assessed. The study includes six key criteria and six variant solutions, all defined according to the same requirements to achieve a minimum thermal transmission coefficient ($U = 0.30\ W/m^2K$), confirming that renewable materials are more economically and environmentally sustainable option for building energy renovation. Sensitivity analysis further examines the threshold at which non-renewable materials become a justified solution, providing useful guidelines for decision-making in practice.*

Keywords *MCDM analysis, thermal insulation, Global Warming Potential (GWP), Super Decisions software, U – value*

1. INTRODUCTION

One of the most effective strategies for reducing energy consumption in buildings located in demanding climatic zones is their energy renovation. A crucial role in this process is played by the proper selection of thermal insulation materials applied to the opaque building envelope. Contemporary insultation market offers a wide range of materials and systems, with the choice being made in accordance with international and national standards, as well as the specific requirements of individual projects. Due to the large number of criteria, making an optimal decision can be challenging, making the application of multi-criteria analysis an extremely useful tool for comparing different influencing factors and predicting their long-term effects. In addition to energy efficiency, a significant aspect in the assessment of thermal insulation materials is their environmental impact, particularly through the analysis of Global Warming Potential (GWP). Recent research has shown that renewable materials such as cellulose and

Corresponding author

MA, Slobodan Peulić
slobodan.peulic@aggf.unibl.org

UNIBL, FACEG
University City, Vojvode Petra Bojovića Blvd.
Banja Luka, RS, Bosnia and Herzegovina

wood fibres have a negative GWP, meaning they absorb more CO_2 during their life cycle than they emit, whereas non-renewable materials such as glass wool, mineral wool, and EPS show significantly higher CO_2 emissions. Beyond the ecological impact, an economic analysis of climate change costs has demonstrated that renewable materials are financially more viable when external CO_2 emission costs are considered.

In the context of European regulations and the growing need for the use of renewable materials, this study applies multi-criteria analysis using Super Decisions software to assess the justification for using renewable versus non-renewable materials in thermal insulation.

The study covers six key criteria and six alternative solutions, with results indicating promising scenarios where renewable materials are a cost-effective and sustainable option in building energy renovation. A sensitivity analysis further examines the threshold at which non-renewable materials become economically and environmentally justifiable solutions.

The modern approach to designing new and renovating existing buildings is increasingly driven by advancements in technology and materials, enabling energy efficiency, durability, and environmental sustainability of structures. However, markets and architectural practices in developing countries, such as Bosnia and Herzegovina, often lag in the implementation of modern materials despite obligations arising from European standards and regulations. The main challenges include high initial costs, limited material availability, insufficient awareness, and inadequate incentives for transitioning to sustainable solutions. Particularly significant in the context of Bosnia and Herzegovina is the expected increase in the application of thermal insulation materials due to increased construction activity and increasingly stringent energy efficiency requirements. Additionally, rising energy costs further emphasize the need for more efficient thermal insulation systems that can reduce heating and cooling consumption and costs. It is crucial to work proactively on introducing new, modern, and renewable materials to facilitate the transition to sustainable solutions. This involves raising awareness among investors, architects, and civil engineers about the benefits of renewable materials. With adequate strategies and support, Bosnia and Herzegovina can leverage global trends in the construction industry and make significant progress toward a more energy-efficient and sustainable built environment.

An analysis of statistical data on energy consumption in Bosnia and Herzegovina further confirms the importance of transitioning to energy-efficient materials and technologies in the construction sector. The introduction of modern materials can not only reduce overall energy consumption but also contribute to achieving European climate goals and lowering costs for end users. According to previous studies covering the Typology of Residential Buildings [1] and the Typology of Public Buildings [2] in Bosnia and Herzegovina, the current state of the construction sector has been analyzed through sample of 2,156 buildings. Based on these data, average U-values of building thermal characteristics have been estimated, enabling a more precise assessment of energy losses and the need for renovation.

According to data from the International Energy Agency, Bosnia and Herzegovina's energy intensity is estimated at 0.40 toe (tons of oil equivalent per 1,000 USD GDP) [3], indicating high energy consumption relative to economic output. It is estimated that as much as 58.44% of final energy consumption belongs to buildings [1], while the remaining portion is distributed among the service sector (14.90%), industry (19.75%), and transport (6.92%). The European Union's statistical office has published data showing that buildings account for 38% of all energy consumption in the EU [4] and contribute to 36% of total greenhouse gas (GHG) emissions [5] [6] [7]. Additionally, in countries with higher energy intensity, energy consumption in buildings exceeds 50% [8]. Comparing the previously mentioned values, there is a noticeable difference of approximately 20% in higher energy intensity in Bosnia and Herzegovina compared to the European standard [9]. As Bosnia and Herzegovina aligns its legislation with EU regulations, an accelerated transition to more sustainable practices is expected. Furthermore, Bosnia and Herzegovina has adopted its Nationally Determined Contributions (NDC), setting an unconditional goal of reducing GHG emissions by 12.8% by 2030 and 50% by 2050, while the conditional target is set at 17.5% by 2030 and

55% by 2050, both compared to 2014 levels [10]. Buildings are among the largest consumers of natural resources and energy, playing a key role in total global CO_2 emissions [11]. Relevant research indicates that the construction sector is responsible for a significant share of raw material, water, and energy consumption, directly contributing to environmental burdens and climate change. A particularly concerning statistic is that residential buildings consume as much as two-thirds of the total energy within the construction industry.

Based on the previously mentioned data, it is evident that reducing energy consumption is necessary for Bosnia and Herzegovina. In this context, the application of appropriate types of thermal insulation during renovation or the construction of new buildings plays a crucial role. The following section will present one possible approach to decision-making regarding the selection of insulation types.

2. ANALYSIS OF THERMAL INSULATION MATERIALS FROM AN ENVIRONMENTAL PERSPECTIVE

Considering previous research, thermal insulation contributes approximately 55% to the construction sector in terms of thermal efficiency improvement in overall heat transfer [12] [13] [14]. Current data indicate that the global thermal insulation market, initially valued at $52.3 billion in 2017, reached $87.2 billion in 2024, with an estimated value of $117.4 billion by 2030 [15]. This growth is primarily driven by the increased use of recycled materials, growing awareness of energy conservation, and rising demand for residential buildings due to population growth and economic expansion, leading to a greater need for thermal insulation materials worldwide [15].

The European Union adopted the New Renovation Wave Strategy of the EU at the end of 2020, which envisions the renovation of the existing building stock with a mandatory application of organic materials [16]. This strategy sets ambitious goals for the modernization and energy renovation of buildings across Europe. Special emphasis is placed on the application of renewable and environmentally friendly materials, which will lead to changes in existing approaches in the construction industry. This strategy promotes a circular economy through material recycling and the use of innovative solutions.

If a comparison is made with Bosnia and Herzegovina, the current practice in the country still relies on non-renewable materials, whose use has a significant ecological footprint throughout their life cycle—from raw material extraction, production, and transportation to installation and disposal after their lifespan. Decisions regarding the selection of building materials are most often based on price and availability criteria, while sustainability, energy efficiency, and environmental impact aspects are frequently overlooked.

One of the significant projects in the popularization of renewable energy solutions was TES Energy – Timber Energy Systems, focused on developing a prefabricated system based on a wooden structure filled with thermal insulation made from renewable materials. The project included an analysis of key criteria, including energy efficiency in production, reduction of toxic substances, installation complexity, maintenance requirements, and the possibility of reusing individual components or the entire system at the end of its lifespan. Special emphasis was placed on the impact of thermal insulation on the environment.

As part of the research, nine types of thermal insulation were analysed based on the criterion of primary energy input required for production from non-renewable sources (Primary Energy Input – PEI (non-ren.) in kWh/m^2), in relation to the total thickness needed to achieve a thermal transmittance coefficient of U = 0.20 W/m^{2}K [17]. The analysis results, shown in Figure 1, indicate that cellulose fibre insulation has the lowest PEI, while phenolic resin insulation has the highest.

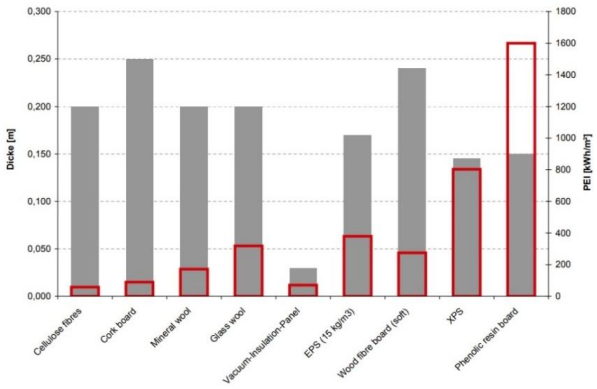


Fig. 1. Primary Energy Input (PEI) of different Insulation Materials to reach U = 0.20 W/m^{2}K [17]

Contemporary material production, in addition to the energy required for their manufacture, also includes the creation of an Environmental Product Declaration (EPD), which analyzes the Global Warming Potential (GWP). This analysis encompasses all stages of the production process from A1 to A3, including raw material extraction, production, and material transport, which is particularly important for thermal insulation. One significant study compared the environmental impact of five types of thermal insulation—cellulose, wood fiber, glass wool, mineral wool, and expanded polystyrene (EPS)—using the example of a newly constructed family house, where the total volume of insulation material was 65 m^3. The GWP analysis results showed that cellulose and wood fiber have a negative global warming potential, meaning that they sequester more CO_2 during their lifecycle than they emit. Specifically, for cellulose (V = 55 kg/m^3), a GWP of -4.526 kg CO_2 eq. was calculated, while for wood fiber (V = 40 kg/m^3), this indicator was -1.918 kg CO_2 eq. In contrast, significant CO_2 emissions were observed for the other analyzed materials: glass wool (V = 24 kg/m^3; 3,607 kg CO_2 eq.), mineral wool (V = 30 kg/m^3; 3.752 kg CO_2 eq.), and EPS (V = 20 kg/m^3; 5.456 kg CO_2 eq.). In addition to the environmental impact, a cost comparison related to climate change caused by CO_2 emissions was also conducted. According to data from the German Environment Agency (UBA Germany), the economic cost of emissions is 237 € per ton of CO_2 eq., leading to the following estimates: cellulose (-1,073 €), wood fiber (-455 €), glass wool (+855 €), mineral wool (+889 €), and EPS (+1,293 €). [18]

These results clearly highlight the importance of material selection in the context of sustainable construction. Natural insulation materials such as cellulose and wood fiber not only have a lower environmental impact but can also help reduce overall CO_2 emission costs, making them a more sustainable solution for long-term planning of energy-efficient buildings.

3. MULTI-CRITERIA ANALYSIS AS A MODEL FOR SELECTING SUITABLE THERMAL INSULATION

Among decision-making strategies, multi-criteria decision-making (MCDM) is a highly effective tool for ranking different alternative solutions based on multiple criteria, with its reliability proven by numerous researchers in various comparative studies [19] [20]. The MCDM method is an analytical procedure that seeks to find the optimal choice among several viable alternatives by considering more than one relevant criterion or objective in the evaluation process [21]. The process of energy renovation of buildings requires compliance with a range of standards and regulations defining technical and environmental requirements. Although certain aspects are regulated by legal frameworks, the architect, as the project leader, has significant freedom in material selection and faces a large number of criteria influencing the final decision.

To facilitate the decision-making process and ensure optimal solutions, applying multi-criteria analysis enables an objective assessment of various factors and their comparison based on defined parameters. Multi-criteria assessment has recently become increasingly important for solving a variety of complex decision-making problems [22] [23] [24]. In the last decade, a multi-criteria assessment has occurred using one of the most essential techniques in energy improvement research, allowing for the comparison of many options [25]. [26]

According to Novak and Skodovsky, a comparison of four thermal insulation systems—mineral wool, polyurethane foam, expanded polystyrene, and phenolic boards—was conducted based on six criteria with assigned weightings:

- material (w = 0.20),
- installation cost required to achieve the prescribed thermal conductivity coefficient (w = 0.35),
- material durability (w = 0.15),
- mechanical properties (w = 0.10), environmental impact (w = 0.10),
- fire resistance (w = 0.10).

Based on this study, polyurethane foam proved to be the most suitable insulation system, while mineral wool was the least adequate. [27] Yilmaz, Özgünler, and Yilmaz analysed five types of insulation (extruded polystyrene – XPS, expanded polystyrene – EPS, rock wool, glass wool, and cellular glass). In analysing a total of 100 scenarios, they used four criteria—energy, cost, thermal comfort, and environmental impact. The results showed

that XPS was the most cost-effective option, followed by rock wool, glass wool, and expanded polystyrene (respectively). Furthermore, the optimal selection was made according to the European Commission's requirements for achieving the nZEB standard (50–70 kWh/m^{2}a), representing a 10% improvement in energy efficiency over the cost-optimal renovation level. [28]

Considering the aforementioned studies, it can be concluded that while the parameters are always related, they are often insufficiently explained in the local context. The first study compared four material types, including six decision-making parameters, while the second included fewer criteria for more insulation types. However, in both cases, the criteria descriptions remained unclear, with insufficiently precise parameter definitions; moreover, neither study provided an explanation of the criteria's significance in the local context. Both studies show similar results, where the most commonly used materials tend to be the easiest to install and the most cost-effective. However, in the context of European efforts to reduce environmental impact, the ranking of criteria and their importance in decision-making should be reconsidered. Based on the results of the TES project and the provisions of the EU's New Renovation Wave Strategy, the following criteria were set for material selection:

- Market availability – Presence and ease of procurement of materials in Bosnia and Herzegovina,
- Ease of installation – Technical complexity and resources required for installation,
- Environmental impact – Ecological footprint of the material, from production to end-of-life,
- Fire resistance requirements – Material fire resistance in compliance with applicable regulations,
- Planned material maintenance – Replacement and maintenance possibilities during exploitation,
- Cost – Material affordability and total implementation costs.

In addition to the criteria analysed using the Super Decisions software, the thermal conductivity parameter was examined to achieve the minimum thermal transmission coefficient of U = 0.30 W/m^{2}K, which is the legal minimum in the Republic of Srpska and Bosnia and Herzegovina. Specifically, to achieve this minimum value, approximately 12 cm of thermal insulation with a thermal conductivity coefficient of λ = 0.041 W/mK is required. Although differences exist in thermal conductivity coefficients, they only affect the insulation layer thickness, which in this case was not considered a determining factor since all insulation types can meet the prescribed minimum standards. This comparison is shown in the table 1.

Table 1. Thickness of TI necessary to reach U_{wall} = 0.30 W/m^{2}K

Insulation	Thermal Conductivity λ [W/mK]	Thermal insulation thickness neccessary to reach U-value (U = 0.30 W/m^{2}K)
Cellulose	0.040	12 cm
Rock wool	0.033	10 cm
Glass wool	0.030	9 cm
XPS	0.034	10 cm
EPS	0.042	12 cm
Phenolic	0.018	6 cm

After the necessary thickness of the insulation material is calculated the average values of GWP for each type of the material is calculated (Table 2).

Table 2. GWP comparison of TI for the house of 300 m^2 gross area with U_{wall}=0.30 W/m^{2}K

Material	Global Warming Potential [kg CO_2 eq/kg]	Density [kg/m^3]	Thickness to reach U = 0.30 W/m^{2}K [cm]	Volume installed [kg]	Total Average GWP [kg CO_2 eq]
Cellulose	-0.635	55	12	1782	-1,131.57
Rock wool	1.93	30	10	810	+1,563.3
Glass wool	2.45	24	9	583.2	+1,428.84
XPS	12.84	45	10	1215	+15,600.6
EPS	4.21	20	12	540	+2,273.4
Phenolic	8.17	45	6	607.5	+4,963.27

Upon analysis of the GWP values, it is noticeable how only cellulose insulation has negative GWP, compared to other materials, what furtherly confirms previous statements and researches. Besides that, XPS showed the worst performance with 18.84 kg CO_2 eq/kg [29], resulting in total of + 15,600.6 kg CO_2 eq

for the installed amount of 1215 kg. Figure 2 shows the ration between GWP impacts among these materials.

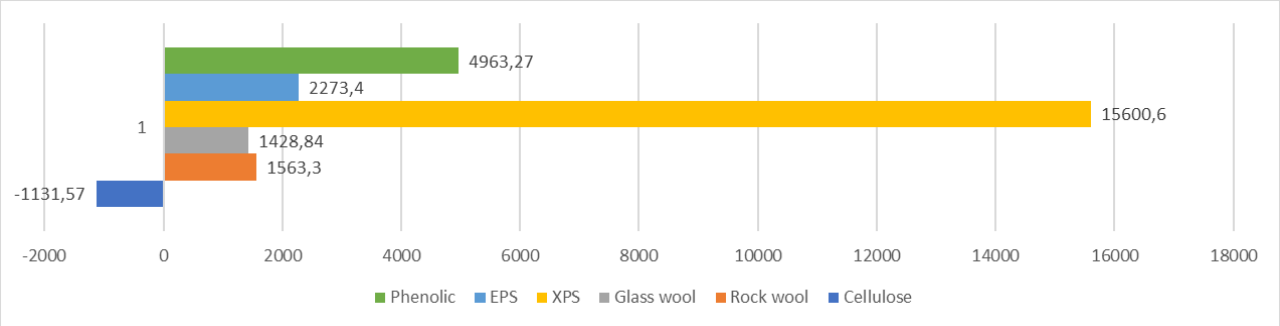


Fig. 2. GWP comparison between different insulation options for an average house of 300 m² gross area, and to reach the U-value of 0.30 W/m²K

When considering the fire resistance of each, it is easier to follow the results for every type of insulation rather than cellulose one. Reason for this is to its' limited market options and lack of studies on its' performance.

The materials in Europe are graded from A to F class (with A being the best, and F the worst) [31]; s1 to s3 smoke production (s1 being low smoke, and s3 high smoke); and d0 to d2 flaming droplets (d0 meaning no material droplets, d1 meaning a few, and d2 potentially dangerous).

ISOCELL made a testing where it is labeled as B-S2, d0 meaning the material contributes little to fire (B class), produces a moderate amount of smoke (S2), and does not form flaming droplets (d0) [30].

It is notable that Glass and Rockwool have the best fire resistance capabilities (ranging between A1 and A2, S1, d0); while Phenolic insulation is graded between B and D class, and XPS and EPS between E and F showing the worst fire resistance capabilities [31].

Each parameter is set as a criterion in the decision-making. The analysis was conducted using the Super Decisions software, version v3.2, which supports decision-making processes. This software includes the Analytical Hierarchy Process (AHP) and the Analytical Network Process (ANP), which are considered the best methodologies for comparing criteria and input data to adequately assess alternatives and predict output results. [32]

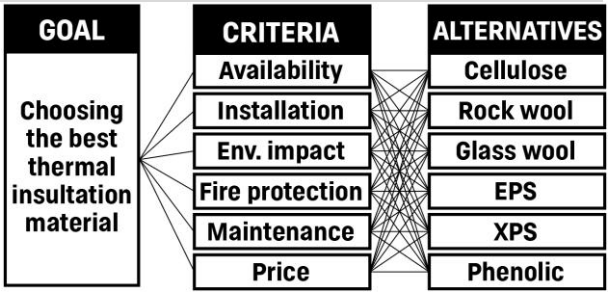


Fig. 3. Goal, criteria, and alternatives setup (author illustration according to setup in Super Decisions software)

Once the parameters were defined, the multi-criteria analysis required a process known as criteria weighting, which involves absolute and relative comparison of the criteria. Weighting allows for determining the significance of each criterion in the final selection of materials, ensuring the objectivity of the decision. In absolute comparison, the six criteria were evaluated based on their contribution to selecting the best solution. Since the aim of this study is to promote sustainable solutions and renewable materials, the environmental impact criterion was established as one of the most important factors in decision-making. The next most important criterion was material maintenance, which includes long-term durability, replacement feasibility, and maintenance costs. The remaining criteria were weighted according to their relevance to building energy renovation. The ranking of criteria and their relative importance are shown in Figure 4.

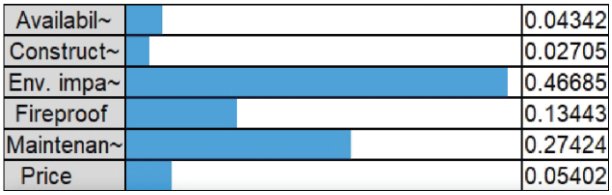


Fig. 4. Criteria ratio in decision making

For the analysis, the most commonly used materials in Bosnia and Herzegovina were selected, as well as those that, although available, are not widely used due to higher costs or more complex installation but which offer better environmental characteristics throughout all life cycle stages – from production and installation to storage after end-of-use. These are shown in Table 3.

Table 3. Compared insulation materials [32, 33]

Cellulose	Rock wool	Glass wool
		
EPS	XPS	Phenolic
		

This analysis provides an overview of the advantages and disadvantages of each option in the context of the specific requirements of energy renovation, offering a foundation for making informed decisions on material selection to ensure long-term efficiency, sustainability, and safety of buildings.

After defining the priorities within each criterion, a comparative analysis of alternative solutions was conducted based on the set criteria. As expected, the results show that expanded polystyrene (EPS) is the most commonly used thermal insulation material on the market in Bosnia and Herzegovina. Its widespread application primarily stems from its economic viability, as it is significantly cheaper compared to other materials with the same purpose, as well as from the fact that its installation is technically simple and quick.

However, EPS simultaneously faces serious environmental challenges. Throughout its entire life cycle – from production and installation to disposal after the end of use – EPS emits a range of toxic substances that negatively impact the environment. This environmental aspect is particularly pronounced in the disposal phase, given its poor biodegradability and potentially harmful emissions during storage or incineration.

Accordingly, the analysis presented in Figure 5 and Figure 6 clearly highlights the extreme values of EPS in two key categories – economic affordability and negative environmental impact. These results confirm the need for a balanced approach when selecting thermal insulation, considering not only the costs of procurement and installation but also the long-term environmental consequences.

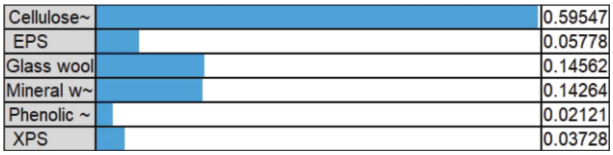


Fig. 5. Environmental impact ratio

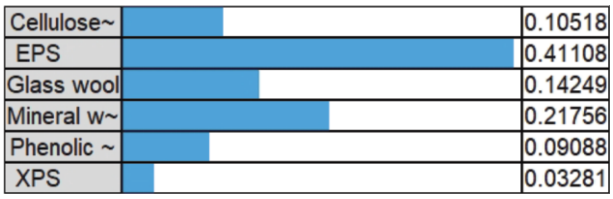


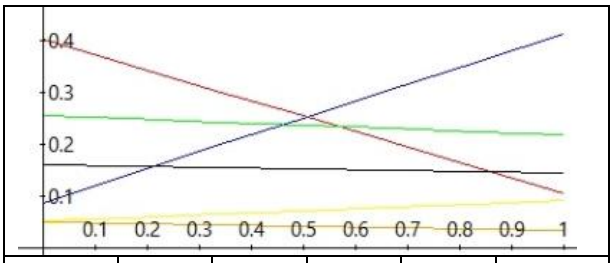
Fig. 6. Price ratio

The results of the multi-criteria analysis indicated that cellulose fibre insulation stands out as the most suitable option, despite being the most financially demanding solution. Although initially more expensive than conventional materials such as EPS or mineral wool, this type of insulation offers numerous long-term benefits that justify the investment. Its greatest advantage lies in its exceptionally favourable environmental profile. Cellulose fibres are derived from recycled paper, meaning their production requires fewer primary raw materials and less energy compared to synthetic insulations. Additionally, their use does not cause the emission of harmful substances during production, installation, and operation, significantly reducing the negative impact on the environment.

When conducting a multi-criteria analysis, a useful tool for assessing the specific importance of each criterion individually is sensitivity analysis. This method reveals changes in the ranking of the best alternatives due to variations in the weight of specific decision-making criteria. The conducted sensitivity analysis showed that changes in the weighting of factors can influence the ranking of materials. Specifically, when price is emphasized as a key criterion, expanded polystyrene (EPS) takes the leading position as one of the most acceptable

options. EPS offers a favourable cost-to-thermal performance ratio, making it an attractive solution, especially for projects with limited budgets. These results highlight the importance of precisely defining priorities when selecting materials, as different weighting scenarios can lead to different recommendations depending on project requirements and financial constraints. Although EPS is more affordable, its justification becomes questionable when considering European legislation and modern practices, which increasingly favor environmentally friendly and sustainable materials, even at the cost of higher initial investments. In this case, it is particularly interesting to observe two parameters that vary the most among the six alternative options—price and environmental impact. When the price criterion exceeds 51% in decision-making weight, EPS becomes the most suitable option; at 57%, EPS and mineral wool emerge as the best choices. The sensitivity analysis is presented in Table 1. This result is notable given that EPS is the most widely used thermal insulation material in the Bosnian market, primarily due to its cost-effectiveness. Although high procurement costs may be a limiting factor, the analysis indicates that cellulose insulation offers the optimal balance between economic viability and environmental sustainability.

Table 4. Sensitivity analysis according to the price criteria

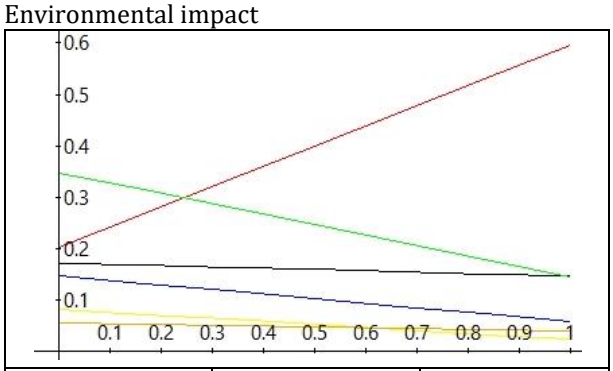


< 21%	21%	46%	51%	57%	> 86%
CF	CF	CF	EPS	EPS	EPS
MW	MW	EPS	CF	MW	MW
GW	EPS	MW	MW	CF	GW
EPS	GW	GW	GW	GW	CF
PH	PH	PH	PH	PH	PH
XPS	XPS	XPS	XPS	XPS	XPS

CF – Cellulose fibres; MW – Mineral wool; GW – Glass wool; EPS – Exapanded Polystyren; PH – Phenolic; XPS – Extruded Plystyrene

The next sensitivity analysis was conducted for the environmental impact parameter. In this case, it is interesting to observe that mineral wool remains the preferred choice until the environmental impact parameter exceeds a weight of 25%. The next significant shift occurs at 62%, when XPS becomes a better option than phenolic insulation, and at 98%, when glass wool surpasses mineral wool as the preferred choice.

Table 5. Sensitivity analysis according to Environmental impact



< 25%	62%	98%
Mineral wool	Celulose fibres	Celulose fibres
Celulose fibres	Mineral wool	Glass wool
Glass wool	Glass wool	Mineral wool
EPS	EPS	EPS
Phenolic	XPS	XPS
XPS	Phenolic	Phenolic

4. CONCLUSION

This paper presented an approach to select thermal insulation in the context of Bosnia and Herzegovina using the multi-criteria analysis tool. Choosing the appropriate thermal insulation plays a key role in the energy efficiency of buildings, especially in a country like Bosnia and Herzegovina, where the construction materials market is undergoing transformation due to integration with European standards and regulations. While traditional materials such as expanded polystyrene (EPS) are widely available and economically affordable, increasing pressure from the European Union to implement renewable and environmentally friendly materials creates opportunities for broader adoption of alternative solutions.

The construction materials market in Bosnia and Herzegovina is characterized by a gradual transition toward more sustainable and energy-efficient technologies, driven by EU regulations and initiatives. Despite this, economic feasibility remains a crucial factor in decision-making.

The application of the multi-criteria analysis method enables a structured and objective decision-making approach, considering various factors such as cost, energy efficiency, durability, and environmental impact. This method provides a clear understanding of the trade-offs between different criteria and helps identify the optimal solution based on set priorities. Specifically, the analysis indicates that if environmental impact is prioritized, renewable materials such as cellulose fibers become the most favorable option. However, if the cost factor exceeds approximately 51% in the overall decision-making process, EPS remains the dominant choice.

This highlights the significant potential for the wider use of renewable materials, particularly if regulatory measures and economic incentives reduce their current market barriers. The introduction of new materials requires a systemic approach, including education, support for manufacturers, and market stimulation through subsidies and tax incentives. Multi-criteria analysis can serve as a useful tool in shaping sustainable construction strategies, enabling decision-making that balances environmental, economic, and technical aspects to achieve the long-term sustainable development of the construction sector in Bosnia and Herzegovina.

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