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MULTICRITERIA ANALYSIS OF ENVIRONMENTAL IMPACT OF DIFFERENT OPTIONS OF EXTERNAL WALLS CONSTRUCTION

WIELOKRYTERIALNA ANALIZA ZRÓWNOWAŻONEGO ROZWOJU ŚRODOWISKA I ENERGETYCZNEJ WYDAJNOŚCI KONSTRUKCJI BUDYNKU

A b s t r a c t

This paper assesses the compositions of exterior wall alternatives of a near zero-energy residential building over environmental profiles, such as embodied energy or embodied CO_2 and SO_2 emissions, by using the LCA methodology ("cradle to gate") as well as over thermal-physical data. The assessment results are calculated by using four methods of a multi-criteria decision analysis. The objective is to optimize the material composition of a constructional design in order to create green Slovak residential construction by the application of natural vegetable materials.

Keywords: building materials, exterior walls, environmental performance, energy efficiency

S t r e s z c z e n i e

W niniejszym artykule ocenione zostają kompozycje alternatyw ścian zewnętrznych w niemal zero-energetycznym budynku mieszkalnym na tle profilów środowiskowych, takich jak energia całkowita czy całkowita emisja CO_2 i SO_2, przez zastosowanie metodologii LCA (w pełnym zakresie) oraz danych termofizycznych. Wyniki ocen obliczane są z zastosowaniem czterech metod wielokryterialnej analizy decyzyjnej. Celem jest optymalizacja materiałowej kompozycji projektu budowlanego w celu stworzenia ekologicznego budownictwa mieszkaniowego na terenie Słowacji przez zastosowanie naturalnych materiałów roślinnych.

Słowa kluczowe: materiały budowlane, ściany zewnętrzne, wyniki środowiskowe, wydajność energetyczna

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1. Introduction to built environment

The rapidly growing human population around the world becomes concerned about environmental issues, including the depletion of natural resources, emissions and pollution, deforestation and soil degradation [1]. Our earth got stressed so much that it retaliated man's unsustainable consumption of its resources. As a result, sudden climate changes cause unprecedented calamities for mankind. Unless the human race learns suitable lessons from nature's fury, further devastation is on the anvil. Of a number of the environmental impacts of development, the one with the highest current profile is global warming which demands changes from the governments, industry and the public. Concerns about the local and global environment situation are rising all over the world. Global warming is the consequence of the long-term build-up of greenhouse gases (CO_2, CH_4, N_2O etc.) in the higher layer of the atmosphere. The emission of these gases is the result of intensive environmentally harmful human activities, such as the burning of fossil fuels, deforestation and land use changes. This is generally considered as the reason for an increase in the average global temperatures by 0.74°C in the last 100 years. The global temperatures are set to rise by further 1.1°C in a low emissions scenario and by 2.4°C in a high emissions scenario by the end of the century [2]. Total greenhouse gas emissions (GHG) in the EU-27 (excluding Land Use, Land-Use Change and Forestry) stood at 5,045 million tonnes of CO_2 equivalents in 2007 [3]. It is well known that the biggest contributor to GHG emissions is the built environment accounting for up to 50% of global carbon dioxide emissions [4]. In addition, the embodied environmental impacts generated by a building during its whole lifecycle can be of the same order of magnitude as those generated during the utilisation stage. The building industry consumes 40% of the materials entering the global economy and generates 40–50% of the global output of GHG emissions and the agents of acid rain [1, 5]. The Europe 2020 Strategy for smart, sustainable and inclusive growth includes five headline targets that set out where the EU should be in 2020. One of them relates to climate and energy: the Member States have committed themselves to reducing GHG emissions by 20%, increasing the share of renewable sources in the EU energy mix to 20% and achieving the 20% energy efficiency target by 2020. In February 2011, the European Council reconfirmed the EU objective to reduce greenhouse gas emissions by 80-95% by 2050 compared to 1990 [6]. The environmental performance of products, services and processes has become one of the key issues in today's world, and it is important to examine the ways in which negative effects on the environment are assessed [1].

Research studies have shown that the initial energy embodied in a building can be as much as 67% of the operational energy over a 25-year period. With growing global concerns over material and resource consumption and the emissions of CO_2 into the atmosphere, the energy embodied in buildings raised in towns and cities becomes one of the key issues that needs to be tackled in the design stages in order to strive towards sustainable buildings design [7]. Asif et al. calculated the CO_2 emissions and embodied energy of eight building materials for dwelling in Scotland: timber, concrete, glass, aluminium, slate, ceramics tiles, plasterboard, damp course and mortar. The case study concluded that 61% of the embodied energy used in a house was related to concrete. Timber and ceramic tiles come next with 14% and 15%, respectively, of the total embodied energy. Concrete was responsible for 99% of the total of CO2 emissions of the home construction, mainly due to its production process [8]. Petersen and Solberg analysed the use of various materials on wood base in place of non-wood materials in Norway. They concluded wood construction to have consistently lower CO_2 eq. emissions than non-wood material [9]. Different types of low-energy houses are built with a variety of descriptive names, such as a passive, zero-energy or self-sufficient house. Most concepts refer to houses constructed with the aim of minimizing the final or purchased space heat demand. This is mainly achieved by improved insulation, reduced air leakage through the building envelope and by heat recovery of ventilation air. These measures result in increased material use and thereby an increased energy use in the production phase. Few life cycle studies have been performed for low-energy and passive houses. Some of them conclude that the operational energy is still the most important, while others show that as much as 40–60% of the total energy use is in the production/construction phases. As the energy for operation decreases, it becomes relatively more important to consider the other phases of a building's life cycle [10, 11]. The Comprehensive European study assessed different types of residential buildings and the results showed that the building envelope had a significant part of the life cycle environmental impacts. The exterior walls and roof were found to be the most important building components [12]. Monteiro and Freire compared the life cycle processes of seven alternative exterior wall solutions for a Portuguese single-family house aimed at identifying environmentally preferable solutions. The results calculated for the three LCIA methods show that the most significant LC phase and process are highly associated with the house operational patterns: for Portuguese houses with reduced HVAC levels, material production becomes the most important process. Concerning the exterior wall scenario analysis, the three LCIA methods indicate that a wooden wall is the preferable solution with the lowest impacts for most categories, whereas alternatives with higher impacts are a double wall with facing brick, a thermal concrete block wall and autoclaved aerated concrete block masonry [13].

This case study is focused on the sustainable or green design of exterior wall construction of a near zero-energy residential building. The environmental performance of alternatives is assessed by using the LCA methodology and their energy efficiency is mainly evaluated in terms of STN 730540 [14].

2. The methods of assessment

2.1. Life cycle assessment

Life cycle assessment (LCA) was developed more than thirty years ago as a tool for analysing environmental issues. It may be used as an instrument for informing and planning, for uncovering "weak points" in the life cycle of products and services as well as for a comparison of possible alternatives. The results of an LCA may be further used to improve the environmental compatibility of products and services [1, 15]. The system boundaries of LCA for this case study are drawn at an appropriate level within the construction phase ("cradle to gate"). The environmental performance of exterior walls is described by the significant indicators: the value of embodied CO_2 eq. (ECO_2), the value of embodied SO_2 eq. (ESO_2) and the total embodied energy (EE). The input data are mainly extracted from IBO-Bauteilkatalog [16]; only straw bales are on the basis of Wihnan's case study [17].

2.2. Thermal-technical assessment

The designed alternatives are compared over thermal-physical data, such as heat transmittance and the phase shift of temperature oscillation which are described in STN 730540 [14], and the calculation of relaxation time (τ) is mentioned. The relaxation time describes the ability of a wall to stabilize the internal temperature. The resultant value of relaxation time depends on the order of particular material layers and creates the concept of temperature inertia. The value is based on the assumption of "stationary cooling" [18].

$$\tau = \sum_{i=1}^{n} (\frac{d_i^2}{2a_i} + \frac{\lambda_i \cdot d_i}{a_i} \sum_{j=i+1}^{n} \frac{d_j}{\lambda_j} \tag{1}$$

where:

d	–	thickness [m],
λ	–	coefficient of heat conductivity [W/ (m.K)],
a	–	temperature coefficient of conductivity [m^2/s)],

2.3. Multi-criteria analysis

The resultant values of the assessment of exterior wall alternatives went through four methods of a multi-criteria decision analysis: Weighted Sum Approach (WSA, value closest to 1.0 = the best), Ideal Points Analysis (IPA, value closest to 0.0 = the best), Concordance Discordance Analysis (CDA, the lowest value = the best) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS, value closest to 1.0 = the best). The weights of particular criteria are solved from the geometric average of line over Saathy matrix [19]. The weights of multi-criteria analyses are: 2.5% for square weight (m), 27.0% for Ψ and τ, 14.5% for EE, ECO_2 and ESO_2. The heat transmittance is not calculated because all the alternatives fulfil almost zero-energy standard and the differences are minimal.

3. Exterior wall alternatives and the results of assessment

The designed construction alternatives are diffusion open, and timber fulfils the load-bearing function in their compositions. The optimization aims at the maximal application of natural, mainly vegetable, materials. Biomass building materials can lock carbon in their mass. Finally, to calculate the CO_2 emissions from material, the carbon emissions are multiplied by the ratio of the molecular weight of CO_2 (m. w. 44) to the molecular weight of carbon (m.w.12): 44/12 [20]. One kilogram of dry vegetable mass contains about 0.5 kilogram of carbon and corresponds with the sequestration of 1.8 kilograms of CO_2. Thus, this quantity is removed from the atmosphere for as long as a plant itself lasts [21].

Alternative 3 expressly achieves the highest value of EE because the materials – wood-fibre insulation and cross laminated wood (CLT) – consume a lot of energy by producing. The wood-fibre insulation participates in 44% of total EE, and CLT participates in 38%. However, CLT assures the elimination of 58% of CO_2 emissions and this alternative achieves high negative balance of CO_2 eq. Alternative 1 represents the lowest absorption of CO_2 eq.

because silicate plaster and plasterboard produce CO_2 emissions, and vegetable material in form hemp (with low bulk density) contributes to low elimination of CO_2. The most suitable alternative is 4 because it expressly achieves the lowest value of total EE and the highest negative balance of CO_2 eq. This alternative can absorb more than 150 kg CO_2 eq. per square meter. The straw material is approximately 75% of the total material composition and participates only in 3% of total EE. This material contributes to the reduction of embodied CO2 eq. emissions by more than 64%. Alternative 4 consists of mainly clean natural materials and presents a return to traditional architecture.

Table 1

Values of environmental indicators

alternative	EE [MJ/m^2]	ECO_2 [kg CO_2 eq./m^2]	ESO_2 [kg SO_2 eq./m^2]
1	876.878	-20.794	0.332
2	496.967	-67.014	0.246
3	1500.233	-119.841	0.668
4	293.001	-154.844	0.168

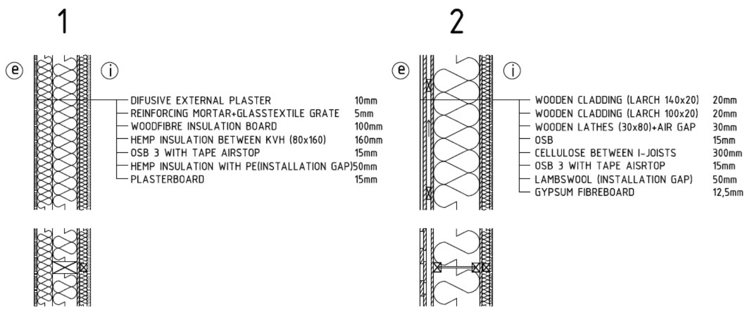

Fig. 1. Material compositions of particular exterior wall alternatives 1 and 2

Rys. 1. Materiałowe kompozycje alternatyw ścian zewnętrznych 1 i 2

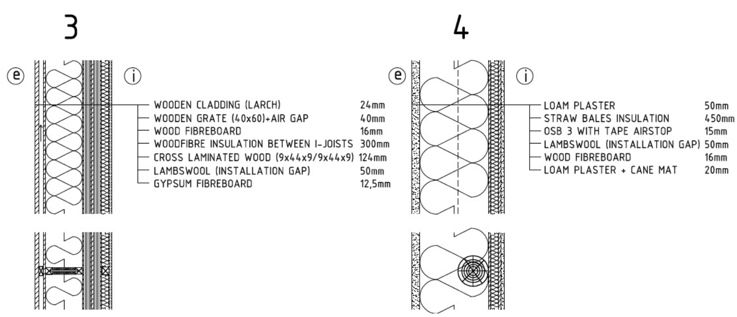

Fig. 2. Material compositions of particular exterior wall alternatives 3 and 4

Rys. 2. Materiałowe kompozycje alternatyw ścian zewnętrznych 3 i 4

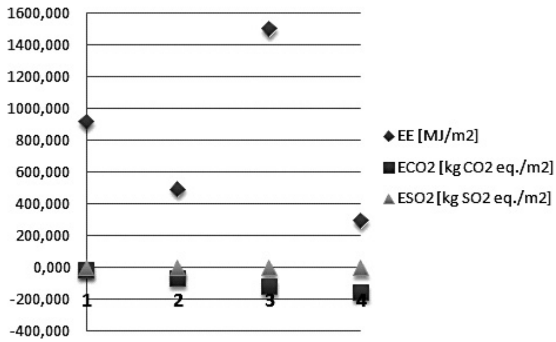

Fig. 3. Environmental profiles of alternatives 1, 2, 3 and 4

Rys. 3. Środowiskowa charakterystyka alternatyw 1, 2, 3 i 4

Table 2

Resultant values of thermal-technical assessment

alternative	*m* [kg/m^2]	*U* [W/(m^2.K)]	Ψ [hrs]	τ [hrs]
1	86.738	0.131	14.459	82.314
2	70.481	0.108	16.040	125.828
3	153.013	0.101	31.385	493.787
4	208.956	0.093	26.319	309.950

All the alternatives fulfil near-zero energy standard. Alternative 4 achieves the highest value of weight per unit area because the straw bales have the bulk density of 100 kg/m^3. This alternative shows excellent values of thermal-technical parameters, such as U, Ψ, τ, being able to assure the stabilization of internal temperature for a long time even if the heating is turned off. Alternative 3 achieves the highest results, mainly in terms of the stabilization of internal temperature. Alternatives 3 and 4 ensure minimal future operational energy for heating and cooling.

Table 3

Resultant values of multi-criteria analysis

alternative	WSA	IPA	CDA	TOPSIS
1	0.184	0.816	4.553	0.251
2	0.374	0.626	3.174	0.392
3	0.658	0.342	2.395	0.604
4	0.774	0.226	1.236	0.711

The alternatives were compared by using four methods of a multi-criteria analysis: WSA, IPA, CDA and TOPSIS. The resultant values of all the methods demonstrate that Alternative 4 is the most suitable in terms of all the evaluated criteria. This alternative markedly improves the total carbon balance and represents a green or sustainable solution for near zero-energy residential construction under the Slovak conditions.

Denotations

EE – embodied energy,
ECO_2 – embodied CO_2 eq. emissions,
ESO_2 – embodied SO_2 eq. emissions,
d – thickness [m],
m – weight per unit area [kg/m^2],
λ – coefficient of heat conductivity [W/(m.K)],
a – temperature coefficient of conductivity [m^2/s)],
U – heat transmittance [W/(m^2.K)],
Ψ – phase shift of temperature oscillation [hrs],
τ – relaxation time [hrs].

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