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Section: Energy for Buildings

Assessment of alternative solutions of lower structure, taking into account energy and environmental impacts

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Abstract

Buildings play significant role in energy consumption and emission production through all phases of life cycle. Over the last decade, the development towards sustainability has become important issue in building design decisions. The relative contribution of embodied impacts of building materials and structures has been recognized as being significant, especially for high energy effective buildings. Life cycle assessment (LCA) belongs to broadly used methodology which helps to make decisions in sustainable building design. The lower structure of buildings consisted of external wall, floor and substructure has by far, the most significant contribution of embodied impacts associated with the construction phase. The goal of this paper is to assess alternative material solutions of lower structure to support decision at the design phase of the project. The solutions are towards reduced embodied environmental impacts and improved energy performance. This study uses life cycle analysis in system boundary from Cradle to Gate and focuses on environmental indicators such as embodied energy and emissions of CO2eq. and SO2eq. The selection and combination of materials influence amount of energy consumption and associated production of emissions during building operation phase. Therefore this study also calculates thermal-physical parameters. Methods of multicriteria decision analysis (MCDA) are used for the interpretation of results of assessments.

Keywords: Lower structure; energy and environmental indicators; thermo-physical parameters; MCDA.

Nomenclature

U	heat transfer coefficient velocity in the direction of (W/(m^2.K))
d	thickness (mm)
c	specific heat capacity (J/(kg.K))
Rh_e/ Rh_i	outdoor/indoor relative humidity (%)
f_{Rsi}	temperature factor to determine mould growth
L_{2D}	linear thermal coupling coefficient
	Greek symbols
ρ	density (kg/m^3)
λ	thermal conductivity coefficient (W/(m.K))
μ	diffusion resistance factor
θ_e/ θ_i	outdoor/indoor air temperature (°C)
Ψ_{2D}	linear thermal transmittance

1. Introduction

Improving energy efficiency in buildings is a major priority worldwide [1]. Sustainable building design, construction and operation require innovations in both engineering and management areas at all stages of a building's lifetime. The lifetime of buildings is composed of a series of interlocking processes, starting from initial architectural and structural design, through to actual construction, and then to maintenance and control, as well as to eventual demolition or renovation of buildings. Inside this lifetime, essential requirements are generated from considerations of social, environmental, and economic issues for high-efficient energy-saving building systems in accordance with Building codes and regulations. In this context, building assessment is becoming popular, in order to have a standard method to evaluate new and existing building design [2]. The importance of the built environment from an environmental impact and energy use perspective is well established.

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High thermal efficiency of the constructed building envelope is a key strategy in the design and construction of buildings, which limit use of active space conditioning systems [3]. Buildings are durable and building decisions have long-term consequences [4]. As a result, design decisions are critical for effective management of future energy requirement [3, 5].

At present, the building sector contributes largely in the global environmental load of human activities: for instance, around 40% of the total energy consumption in Europe corresponds to this sector. It also represents a major target for improvement, and is generally addressed by most environmental policies [6]. Buildings themselves also produce approximately 30% of CO_2 emissions and up to 40% of total waste [7], [8].

The so-called low carbon buildings, based on LCA (Life Cycle Assessment), is point to the buildings that we refer to the least carbon dioxide emissions to the biosphere throughout their life cycle from design, construction, operation, until the destruction as important evaluation criteria. "Low-carbon building" is the advanced reflection of current "green building" [9]. LCA is an objective process for evaluating the environmental loads associated to a product, process or activity by identifying and quantifying the use of mass and energy and the discharges to the environment [10]. LCA accounts for all energy inputs and outputs of a building during its entire life cycle, including manufacturing, use, and demolition phases [11].

The identification of the building sector as one of the key consumers of energy led to the creating of some rules that are targeted at improvement in the energy performance of buildings towards to near zero energy performance buildings, through the reduction of energy consumption during the occupation phase [12]. This energy consumption of building is considered as the energy that is used to maintain the occupants' comfort inside building (operational energy for heating, cooling, lighting, etc.). When taking entire building life cycle perspective into account, total used energy includes operational and embodied energy [13]. The energy needed for operations can be reduced considerably by improving the insulation of the building envelope, technical solutions, etc. By decreasing energy demand for operation it is necessary to pay more attention to the energy use for the material production, which is the embodied energy [14].

The aim of this study is analysis of environmental indicators such as embodied energy and emissions of $CO_{2eq.}$ and SO_{2eq} as well thermal-physical parameters for alternative solutions of lower structure.

2. Methods of research

Environmental indicators are calculated by the Life Cycle Assessment method [15]. The analysis investigates the role of different building material compositions in terms of the embodied energy from non-renewable resources and the embodied equivalent emissions of CO_2 and SO_2 in nearly zero energy buildings. Embodied energy (EE) is the energy utilized during manufacturing stage of building materials and represents the energy used to acquire raw materials (excavation), manufacture and transport. The CO_2 emissions (ECO_2 – global warming potential GWP) and SO_2 emissions (ESO_2 – acidification potential AP) represent the equivalent emissions within the LCA boundary – Cradle to Gate. The input data of these indicators are extracted from the LCA database – IBO [16]. In this study, it is also calculated environmental indicator ΔOI3. The ΔOI3 indicator for one building material layer indicates by how many OI3 points that layer of building materials raises the $OI3_{KON}$ of a structure. In other words, if we eliminate one layer from a structure the $OI3_{KON}$ of the structure will sink by ΔOI3points. The ΔOI3 indicator is calculated according to equation (1) [17].

$$\Delta OI3 = \frac{1}{3} \cdot \left[\frac{1}{10} \cdot \left(EE_{BM} \right) + \frac{1}{2} \cdot \left(ECO_{2BM} \right) + \frac{100}{0,25} \cdot \left(ESO_{2BM} \right) \right] \tag{1}$$

where:

EE_{BM} – embodied energy of one structure layer – building material [MJ/m^2];
ECO_{2BM} – embodied emissions CO_2 of one structure layer – building material [kg CO_{2eq}/m^2];
ESO_{2BM} embodied emissions SO_2 of one structure layer – building material [kg SO_{2eq}/m^2].

For purpose of reduction of future energy demand, these wall assemblies of alternatives are designed to meet requirements for nearly zero energy houses (U= 0,15 W/(m^2.K) according to STN EN 73 0540). The thermal-physical parameters are calculated for Slovak climatic conditions (STN EN 73 0540):

θ_e – outdoor air temperature (–13 °C);
θ_i – indoor air temperature (20 °C);
Rh_e – relative air humidity in outdoor (84%);
Rh_i – relative air humidity in indoor (50%).

The most of aspects are calculated by using software Svoboda – Area 2009 and according to STN 73 0540. The designed structural detail of the contact base, external cladding and slab on ground is evaluated by the calculation program Psi-THERM 2D. Psi-Therm software is tool available for the analysis of thermal bridges in construction components. This powerful design tool is validated to ISO 10211 and BR497. The software produces U-values, Psi-values and $f_R$si-values [18]. This software was used because of its suitability to evaluate the thermo technical properties of building structures and their structural details.

Outside air temperature calculated in the winter to shall designate the location of the building, depending on the geographic location according to maps of temperature fields and, depending on altitude Kosice of 297 m above sea level (2. temperature region), θe = –13 °C. Calculated relative humidity of ambient air is determined by the ambient temperature as calculated φe = 84%. Internal air temperature for the residential part of the building is θi = 20 °C. Relative humidity of indoor air is φi = 50%. Surcharge for heating temperatures dipped to decrease indoor air is to 5 K. Thermal-physical parameters for evaluated alternatives are presented in the Table 1.

Table 1. Basic physical parameters of lower structures

An example of a column heading	U_{wall} ($W/m^2.K$)	U_{floor} ($W/m^2.K$)	θ_{si} (°C)	f_{Rsi} (–)	L_{2D} (W/m.K)	$L_{2D,\,wall}$ (W/m.K)	$L_{2D,\,floor}$ (W/m.K)	Ψ_{2D} (W/m.K)
A – Ytong P2-400, expanded polystyrene EPS 70F B – Thermal insulation – EPS 100 S, concrete slab, gravel bed C – Extruded polystyrene, concrete shuttering blocks, strip footing	0.104	0.170	17.73	0.93	0.527	–0.260	–0.256	0.0118
A – Ytong P2-400, expanded polystyrene EPS 70F, foam glass block B – Thermal insulation – EPS 100 S, concrete slab, gravel bed C – Extruded polystyrene, concrete shuttering blocks, strip footing	0.104	0.170	18.06	0.94	0.514	–0.260	–0.256	–0.0016
A – Ytong P2-400, expanded polystyrene EPS 70F, foam glass block B – Reinforced concrete slab, thermal insulation – XPS C – Gravel bed	0.104	0.103	18.31	0.95	0.462	–0.260	–0.154	–0.0486

Through the analysis of each construction details is shown the effect of the position of building materials in structure, mutual combination of thermal insulation, as well as the overall solution and proper design of construction details. In this case the contact details of the external wall, the floor and the substructure are evaluated in terms of thermal physical parameters and environmental indicators.

3. Results and discussion

In the figure (Fig. 1) is shown the first variant of lower structure with thermal insulation. Variant 1 is the most widely used method of building foundation, which does not meet requirements for energy efficient buildings. Thermal insulation of external walls continues until the lower edge of the base strip. Thermal insulation in the floor is laid on the upper surface of the concrete slab. Thermal insulation of external walls and the floor is separated by bearing structure.

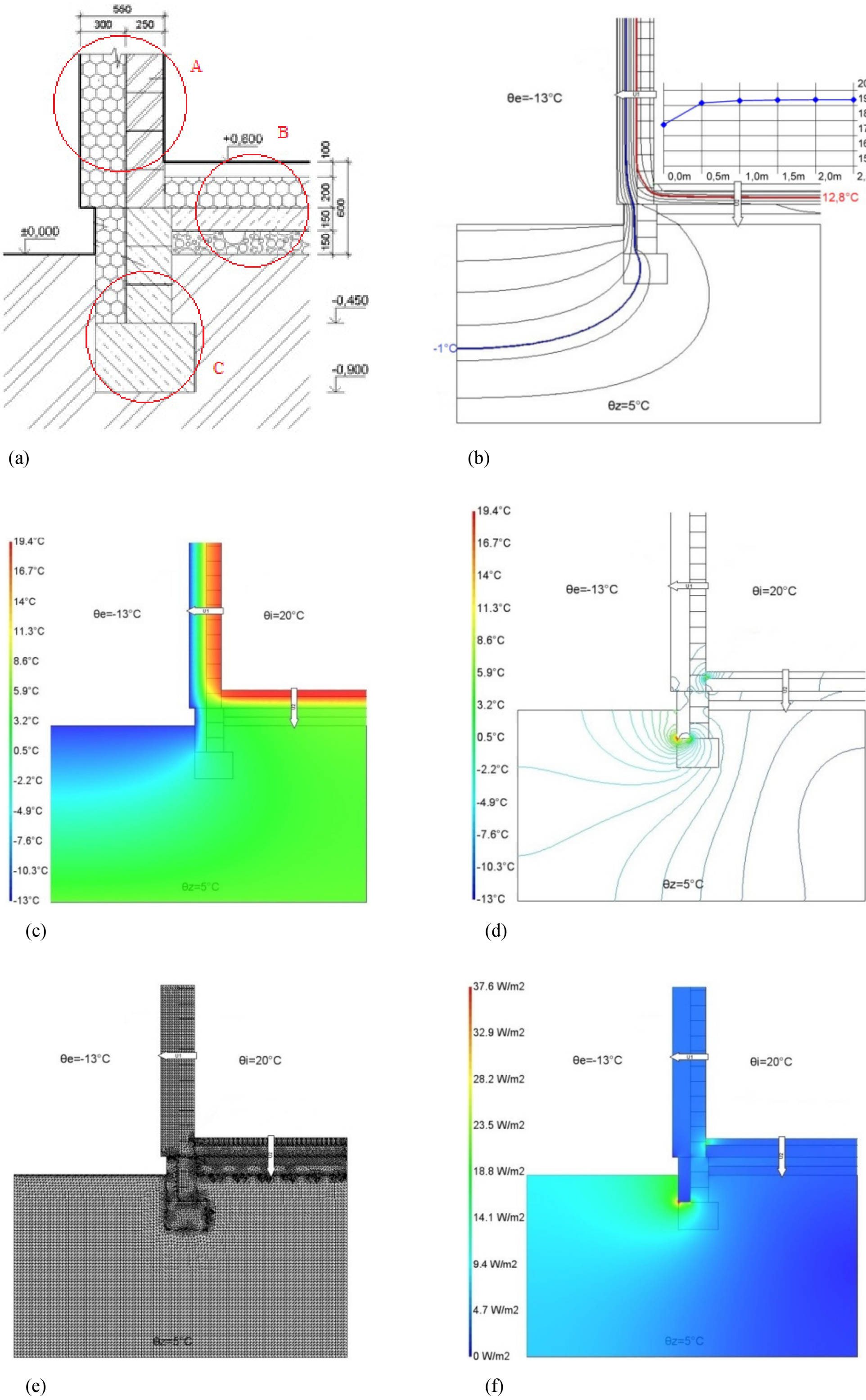

Fig. 1. Variant 1 Detail of basement with thermal insulation (a), course of isotherms of –1°C and 12.8°C (b), thermal field (c), thermal loss (d), network (e) and simulation of thermo vision (f) in the structural detail of the contact base, external cladding and slab on ground

In the figure (Fig. 2) is shown the variant of lower structure with foam glass block and thermal insulation. Thermal bridge, which forms the bearing structure in contact with the base plate can be interrupted using polystyrene-concrete shapes, respectively blocks of foam glass. These methods of foundation can still be combined with insulation plinth, respectively without insulation footing part.

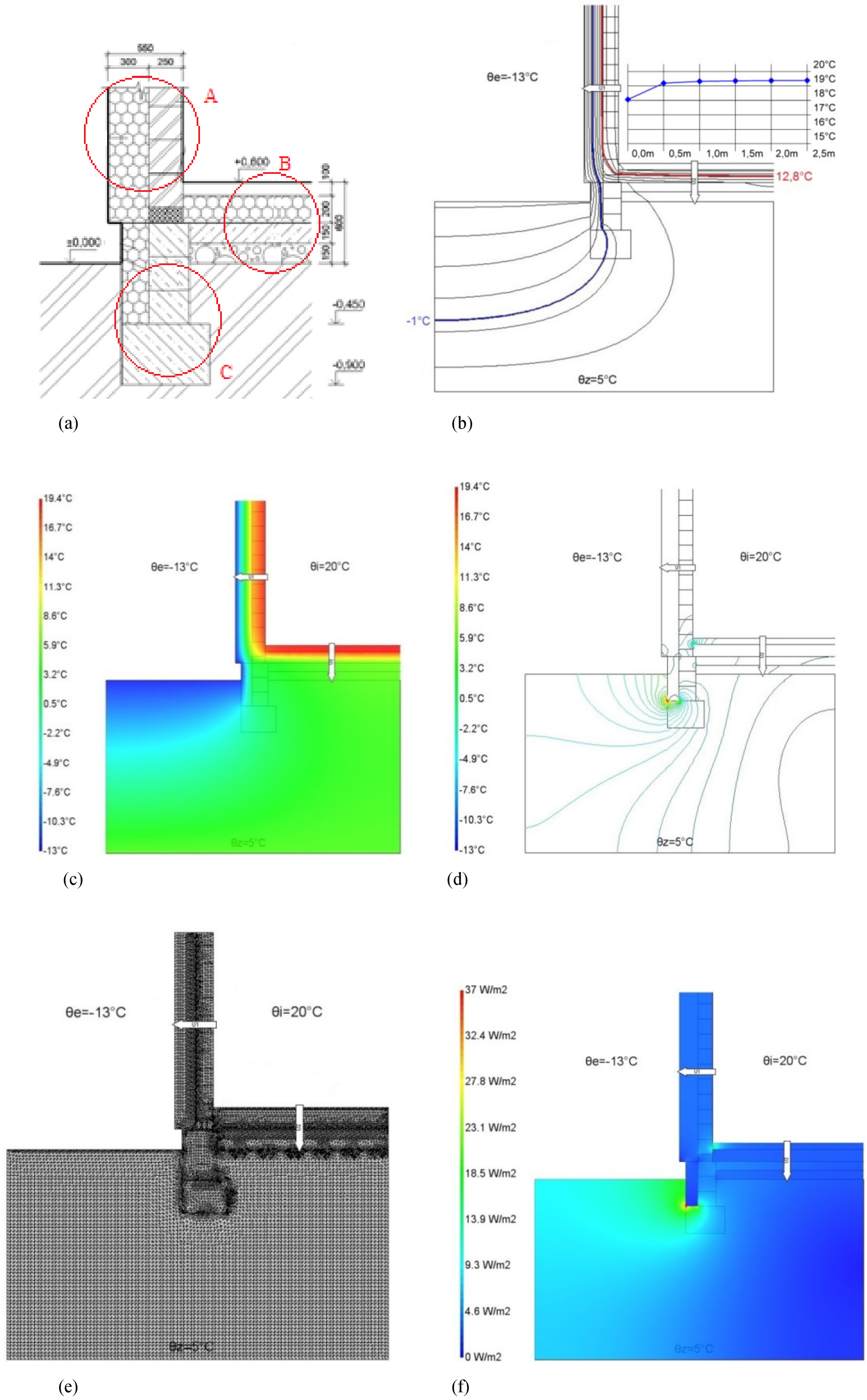

Fig. 2. Variant 2 Detail of basement with foam glass block and thermal insulation (a), course of isotherms of –1 °C and 12.8 °C (b), thermal field (c), thermal loss (d), network (e) and simulation of thermo vision (f) in the structural detail of the contact base, external cladding and slab on ground

In the figure (Fig. 3) is shown variant of lower structure on foundation tank of extruded polystyrene. The second, a relatively new way of foundation is based on the tank from extruded polystyrene. First, there was prepared a suitable base that can form, for example compacted embankment of gravel. On the prepared surface are first fitted the side panels of extruded polystyrene (XPS). Subsequently, the individual sheets of XPS are putted on the bottom of the foundation tank. Reinforced concrete base plate is made to the upcoming foundation tank.

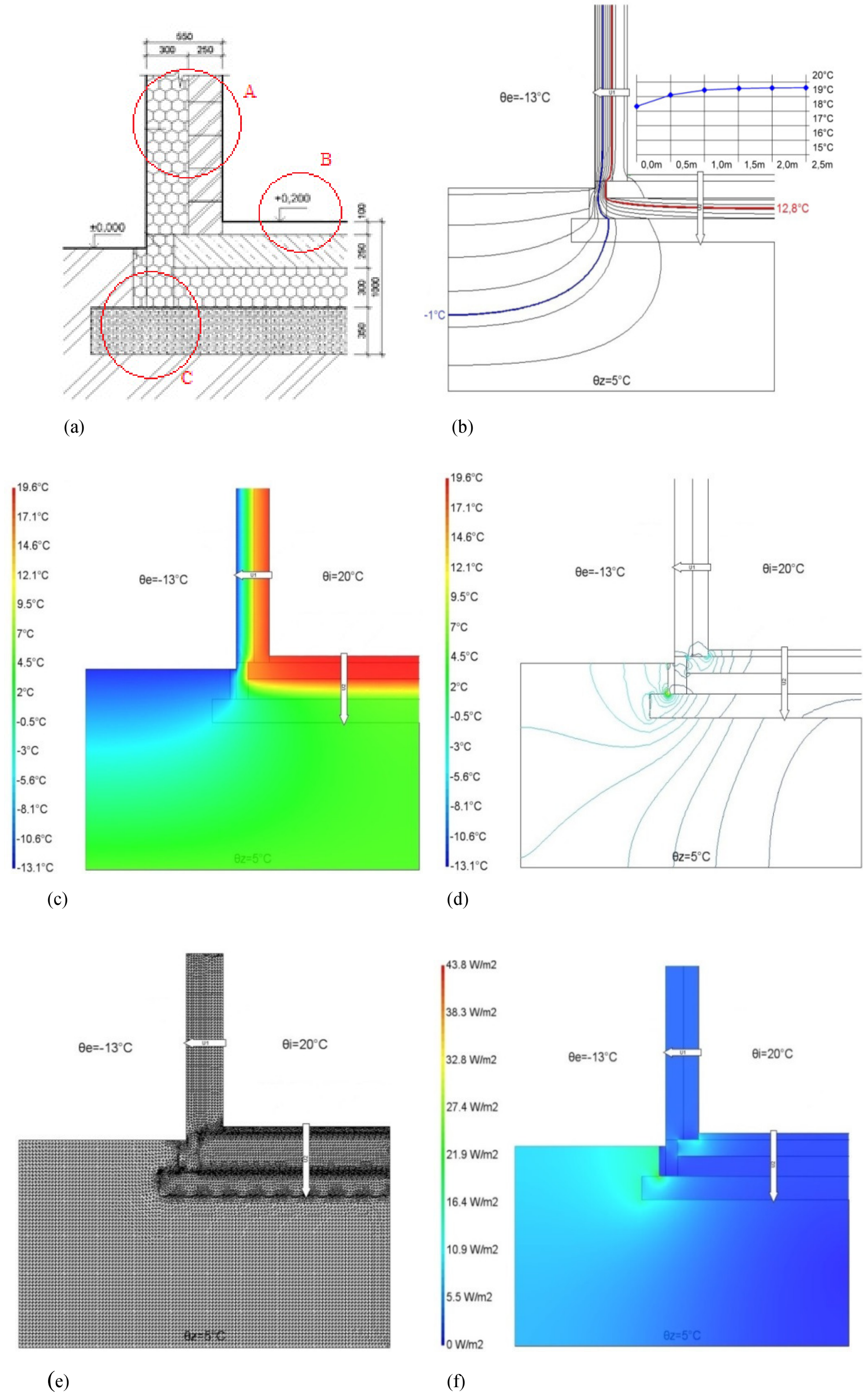

Fig. 3. Variant 3 Detail of foundation tank from extruded polystyrene with foam glass block and thermal insulation (a), course of isotherms of –1 °C and 12.8 °C (b), thermal field (c), thermal loss (d), network (e) and simulation of thermo vision (f) in the structural detail of the contact base, external cladding and slab on ground

From the analysis of structure details (Fig. 1–3) follows that the hygienic requirements for minimum surface temperature $\theta_{si,N}$ = +12,80 ºC in Slovak climatic condition are met in all variants of details.

The results of environmental indicators in terms of total values per square meter are illustrated in the Figure 4. The environmental evaluation results and environmental profiles of lower structure alternatives show that alternative 3 achieves the lowest values of EE, ECO_2 and ESO_2. Exterior wall 3 can assure the highest reduction of EE by 23.15% – 25.3%, of CO_2 by 12.2% – 14.6%, of SO_2 by approximately 24.15% – 25.85% in comparison with other alternatives.

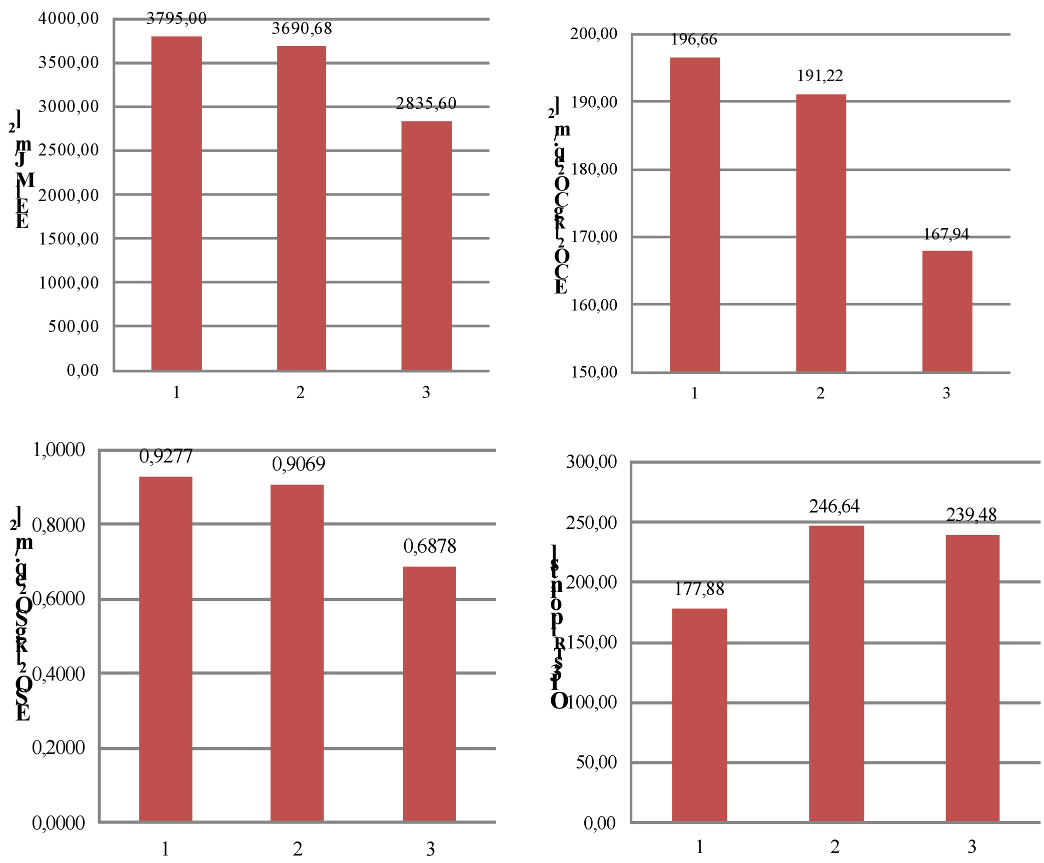

Fig. 4. Embodied energy, CO_2 emissions, SO_2 emissions and $OI3_{STR}$

The variants of lower structures are evaluated in order to obtain total score from assessment results and to indicate the best option. The results are compared through mathematical methods Weighted Sum Approach (WSA) or Simply Additive Weight (SAW) [19], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [20], Ideal Points Analysis (IPA) and Concordance discordance analysis (CDA). Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is developed by Yoon and Hwang [21]. The basic concept of this method is that the selected alternative should have the shortest distance to the positive ideal solution and the farthest distance from the negative ideal solution [21]. This method assumes that each criterion tends toward a monotonically increasing or decreasing utility [21, 22]. The IPA rests upon the deviation between the set of ideal solutions and the set of effective solutions. Although the ideal solution surely almost does not exist, it serves as an important reference model. The best compromise solution is determined as that solution that is the nearest to the ideal one. The increasing distance from the ideal solution for factors located upper on the scale of importance induces greater consequences than the increasing distance from the ideal solution for factors located lower on the scale of importance [23]. The CDA is a method consisted of comparison of alternatives of pair selection. It measures the degree by which the alternatives of selection and the weights of factors prove or disprove the ratio between the alternatives. The differences in the weights of factors and in the evaluations of criteria are analyzed by means of the procedures of concordance and discordance separately [23]. The WSA method comes from principle of maximization of benefit, simplification of this method is that it is assumed only linear function of benefit. Process of this method is comfortable to IPA method; resulting sequence of alternatives is opposite [23].

The best value of total score for methods WSA and TOPSIS is the number nearest to 1.0, for IPA is the number nearest to 0.0 and for CDA is the lowest number. The weighting of assessed aspects is calculated by using Saaty's method in order to elimination of subjectivity [24].

The variant 2 achieves the worst results of MCDA. The material composition of variant 3 represents the best solution in terms of value of total score of MCDA according to using mathematical methods as seen in Table 2.

Table 2. Results of MCDA for variants of lower structures

	1. (Variant 3)	2. (Variant 1)	3. (Variant 2)
CDA	0	1.8913	3.1895
IPA	0	0.8634	1
WSA	1	0.1366	0
TOPSIS	1	0	0

4. Conclusion

The goal of this paper was assessment of alternative material solutions of lower structure to support decision at the design phase of the project. The solutions were towards reduced embodied environmental impacts and improved energy performance. This study used life cycle analysis in system boundary from Cradle to Gate and focused on environmental indicators such as embodied energy and emissions of CO_2eq. and SO_2eq. The selection and combination of materials influence amount of energy consumption and associated production of emissions during building operation phase. Therefore this study also calculated thermal-physical parameters. Methods of multicriteria decision analysis (MCDA) were used for the interpretation of results of assessments.

The variant 3 of lower structure founded on the tank from extruded polystyrene is evaluated as the best solution. The higher values of embodied energy and CO_2 and SO_2 emissions are caused by the concrete shuttering blocks and strip footing in variants 1 and 2. The future research work will be aimed to evaluation of more variants of lower structures in term of thermal physical properties of used materials as well their embodied energy and emissions.

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