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Article

Optimization of Construction Compositions for Design of Green Building

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Abstract: The building sector and its products are generating worldwide substantial environmental impacts. It is known that the building sector represents approximately 40% – 50% of the total energy consumption and production of emissions in developed countries. It is recognized that operational energy analysis has dominated building energy research for many years when compared to embodied energy analysis. It has been shown, that the building becomes more operationally energy efficient, the embodied energy to operational energy ratio increases. The embodied energy and emissions are therefore likely to account for an increasingly large proportion of building-related life cycle CO_2 eq. emissions in the future. The paper presents results of environmental and thermal-physical analyses of the designed building constructions. This study provides environmental assessment of used building materials in construction variants by methodology LCA. The results prove that natural plant building materials serve as a long-term carbon store and ensure elimination of carbon footprint of building. The thermal-physical assessment of construction alternatives is analyzed for the purpose of assuring positive effect on all-season energy balance of the operation of residential building in climatic conditions of Slovakia. The result of multi-criteria analysis of construction compositions demonstrates one possible way of creating green residential building which is assessed by partial analyze of LCA at the conclusion of the paper.

Keywords: building constructions, embodied energy, embodied CO_2 eq. emissions, LCA

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1. Introduction

The building industry and its products (buildings) are associated with a number of environmental burdens which vary from one context to the other. These effects include the energy consumption, greenhouse gas emissions, land degradation, ecosystem destruction [1, 2]. The building constructions consume a large amount of resources and energy and, owing to current global population growth trends; this situation is projected to deteriorate in the near future. The anticipated growth in global population from 6.5 billion in 2005 to approximately 9.0 billion in 2035 indicates the grave situation of material and energy consumption as a result of the anticipated increase in construction activities [3]. It is estimated that buildings account for approximately 40% of the total energy use in Europe and for about 36% of the EU's total greenhouse gas emissions, including the existing energy conservation in buildings [4]. During 2004, buildings alone depleted nearly 37%t of the global energy supply and emitted 32% of all CO2 emissions. These shares will grow: in 2030, buildings are expected to contribute 35-42% to global CO2 emissions [5].

The European Council reconfirmed in February 2011 the EU objective of reducing greenhouse gas emissions by 80-95 % by 2050 compared to 1990, necessary reductions according to the Intergovernmental Panel on Climate Change by developed countries, in order to keep climate change below 2 ºC. This is in line with the position endorsed by world leaders in the Copenhagen and the Cancun Agreements. These agreements include the commitment to deliver long-term low carbon development strategies [6]. In the industrialized world, the issue has been extensively addressed in terms of reduction of operating energy needs and, to a lesser extent, concerning the embodied energy of building materials and processes [7].

The energy flows in buildings may be looked from two different perspectives. Firstly the embodied energy that goes into the construction of the building using a variety of materials. Secondly the operation energy that is required to create a comfortable environment within the building during its lifetime [8]. The embodied energy of a residential building is estimated at 20-40% of operation energy over its total usable life. However, this varies from one context to the other due to the primary energy used, technological advancement of a particular context and the methods used for the inventory analysis [9]. The energy life cycle analysis of buildings concluded from case studies Ramesh et.al., that operation energy has major share 80–90% in life cycle energy use of buildings followed by embodied energy 10–20%, whereas demolition and other process energy has negligible or little share [10]. Ding suggests that the production of building components off-site accounts for 75% of the total energy embedded in buildings and this share of energy is gradually increasing as a result of the increased use of high energy intensive materials [11]. Vonka's case study of the residential buildings has shown that embodied energy can account for 20% and less of the total energy consumption during the life cycle (considered 80 years) [12]. Sixty studies of different buildings located in 9 countries (for example Sweden, Germany, Australia, Canada and Japan) have been performed and found that the proportion of embodied energy in materials used and life cycle assessed varied between 9% and 46% of the overall energy used over the building's lifetime when dealing with low energy consumption buildings (with good thermal insulation, adequate orientation, passive conditioning, etc.) and between 2% and 38% in conventional buildings. The lifetime of evaluated buildings usually considered is 50 years [13]. However, energy saving measures, like the additional insulation of the building envelope, change of windows or the installation of solar collectors, photovoltaic panels, etc. usually contribute to the reduction of operational energy, and indirectly to the reduction of emissions, but at the same time increase the embodied energy of the building [12]. It is obvious that the more energy needed for operation decreases, the more important embodied energy (and related embodied emissions) is to pay attention. The embodied energy and emissions are therefore likely to account for an increasingly large proportion of building-related life cycle CO_2 eq. emissions in the future.

For conventional dwellings in Belgium that comply with the legal energy performance level, the total embodied energy corresponds to 1/3 - 1/4 of the operational energy consumption during 30 years of use of the building, is seen in Table 1. Only extremely low energy buildings might have the total embodied energy higher than the energy use of the utilization phase. However, the sum of both embodied energy and operational energy consumption during usage remains much smaller for extremely low energy dwellings than for average dwellings [14, 15].

Table 1. Embodied energy (EE) and operational energy (OE) consumption in 30 years for all calculated variants of typical Belgian residential buildings.

	Non-insulated variant		**Variant according to legal requirements**		**Extremely low energy variant**	
	EE [MJ/m^3]	**OE [MJ/m^3]**	**EE [MJ/m^3]**	**OE [MJ/m^3]**	**EE [MJ/m^3]**	**OE [MJ/m^3]**
Terraced house	560–600	5800–9200	600–790	3850–4660	910–940	880–910
Semi-detached house	690–730	9400–13000	710–860	5100–6300	1080–1150	960–1050
Detached house	780–915	7500–13200	800–900	3050–5000	1060–1230	830–1040
Non-compact house	890–1160	11800–27000	990–1240	4500–5400	1190–1400	920–1170

The heavier weight of constructions showed reduced operational CO_2 eq. emissions in case studies in UK. All the heavier weight cases were found to have lower CO_2 eq. emissions than the equivalent lightweight timber case, ranging from a 7% saving (medium weight mixed-mode case) to a 17% saving (heavyweight fully air-conditioned case). This was primarily due to the dynamic thermal storage provided by the thermal mass improving the energy efficiency of both heating and cooling modes of operation and also, importantly, improving the passive summertime performance, thereby delaying the point in the lifecycle at which occupants might be likely to seek to air condition their homes. The inclusion of thermal mass delayed the year in the lifecycle when this occurred, due to the better passive control of summertime overheating. Operational heating and cooling energy needs were also found to decrease with increasing thermal mass due to the beneficial effects of fabric energy storage [16].

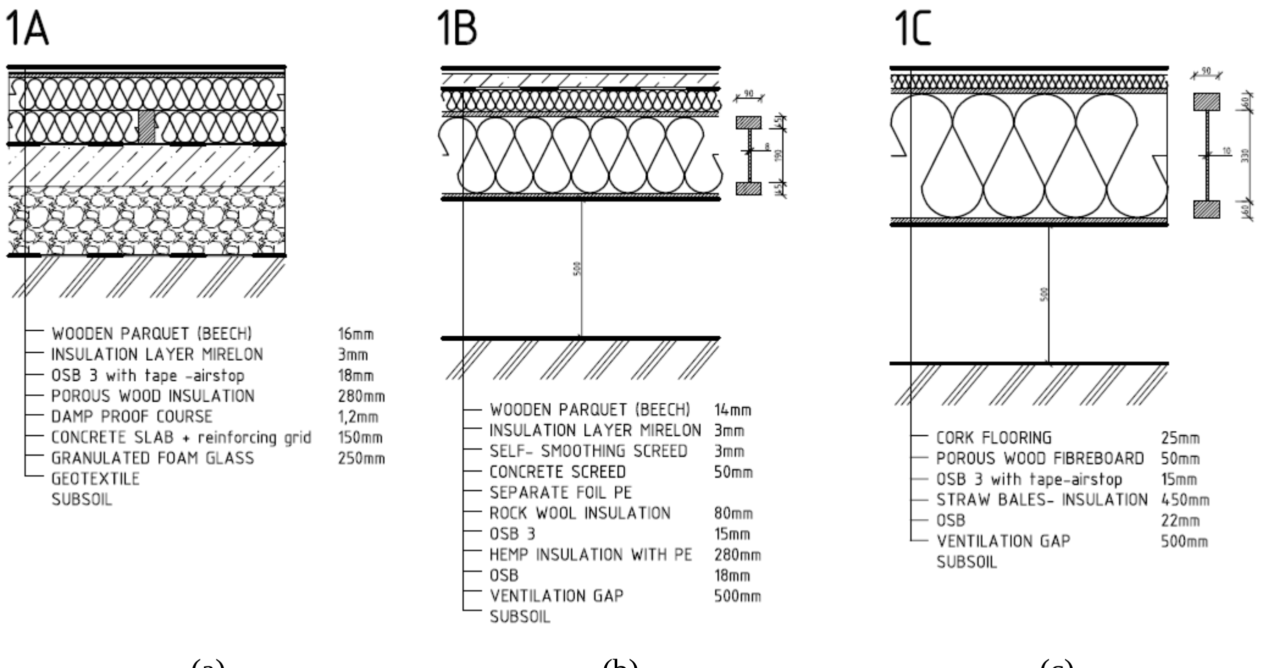
In this case study analyze environmental quality and selected thermal-physical parameters of designed construction compositions in order to create sustainable building constructions for climatic conditions of the Slovak republic. Selection of building materials determines initial level of embodied energy and predicts future energy consumption. The aim of comparisons of environmental profiles of construction alternatives is presented high environmental performance, energy efficiency and healthy envelope of wood-framed residential building. It is the fact that wood-framed construction requires less energy, and emits less CO_2 eq. emissions to the atmosphere, than other construction. The buildings can make a marked contribution to energy and carbon conservation by sophisticated building design.

2. Methods

The field of building environmental assessment has become a popular research area over the past decade. One of the basic environmental methodologies is the Life Cycle Assessment (LCA), which is described in a set of international standards ISO 14040-49 and is applicable to any product of human activity. The environmental quality can be described in the wide range of applications using recently, the most accepted equivalent environmental criterions, such as the value of embodied CO_2 eq. emissions (Global Warming Potential - GWP, from a global point of view,), the value of embodied SO_2 eq. emissions (Acidification Potential - AP, from a regional point of view) and the embodied energy from non-renewable resources. The data of the environmental indicators for building materials are extracted from available databases: IBO –Bauteilaktalog and Öbox, only for straw bales is on basis Wihnan's case study [17]. The goal of this partial LCA analysis is to provide guide for decision-making according to the values of different environmental performance of building constructions for future choice of material base in preparatory phase of building project.

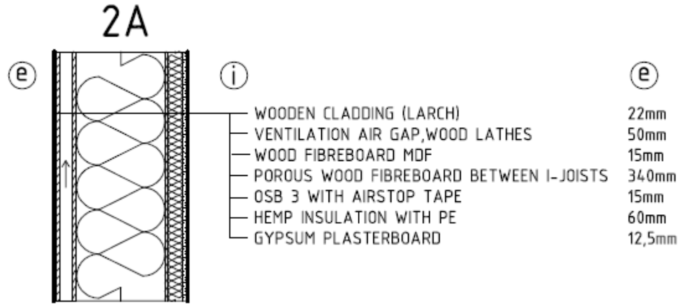
The optimization of construction alternatives for floor (Figure 1), for external wall (Figure 2) and for roof (Figure 3) is based on maximal using nature plant building materials which lock carbon in their mass. Each kilogram of dry plant matter contains about 0.5 kilograms of carbon. This corresponds to sequestration of approximately 1.8 kilograms of CO_2 from the atmosphere through photosynthesis [18]. This quantity is thus removed from the global atmosphere for as long as the plant itself lasts – until it rots or burns.

Figure 1. Composition of floor construction above ground for (a) alternative 1A (b) alternative 1B (c) alternative 1C

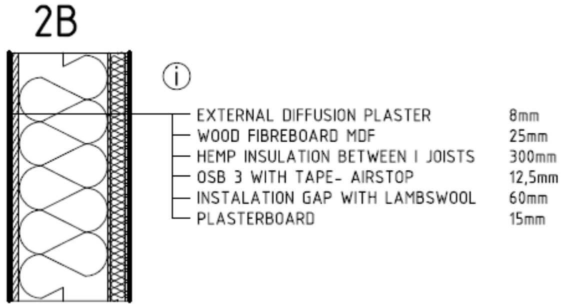


(a) (b) (c)

Figure 2. Composition of external wall construction for (a) alternative 2A (b) alternative 2B (c) alternative 2C



(a)



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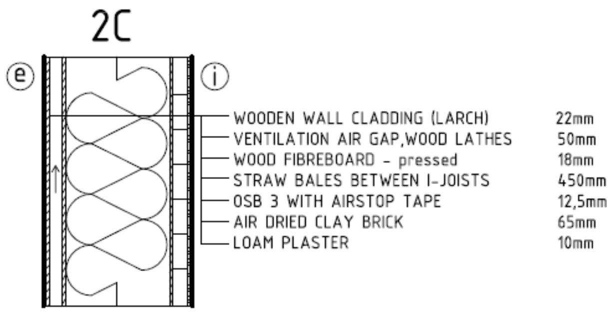
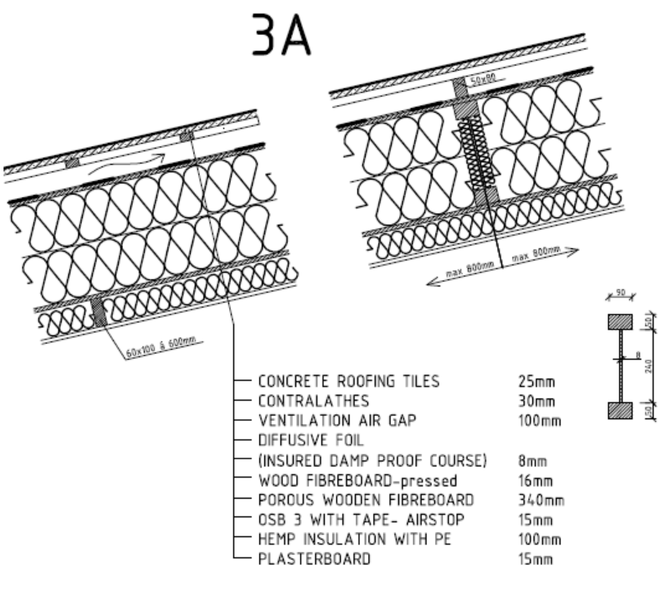
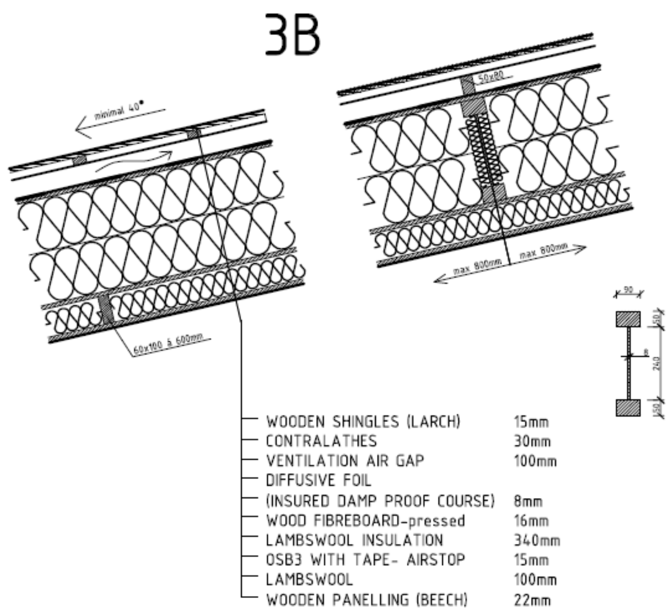


(c)

Figure 3. Composition of roof construction for (a) alternative 3A (b) alternative 3B (c) alternative 3C



(a)



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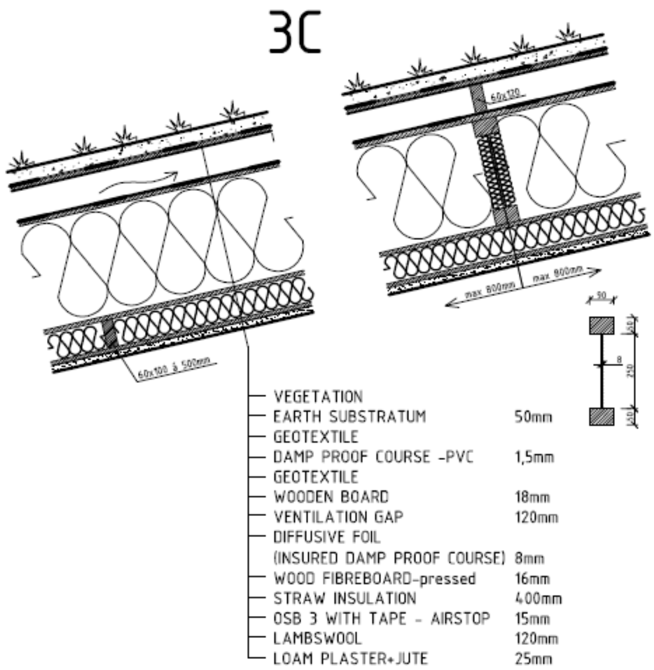
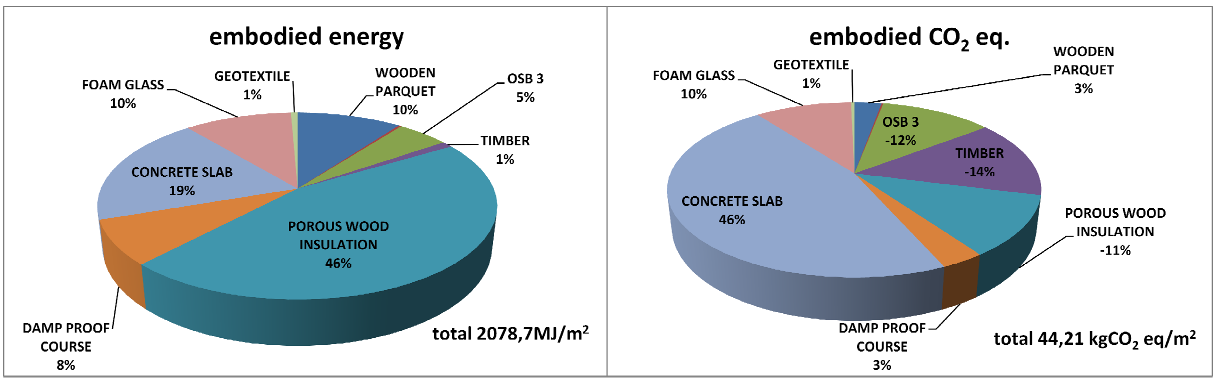


(c)

The particular alternatives of construction compositions are evaluated in terms of significant environmental indicators: embodied energy from non-renewable resources, embodied CO_2 eq. emissions and embodied SO_2 eq. emissions by methodology of LCA with boundary "Cradle to Site". The amount of emitted emissions to atmosphere during production phase of material depends mainly on amount of energy consumption. The highest quantity of used building materials is calculated for thermal insulations and therefore the insulation materials should achieve the highest values of initial embodied energy and emissions. However, it isn't valid for some evaluated construction alternatives as seen in following figures 4-12.

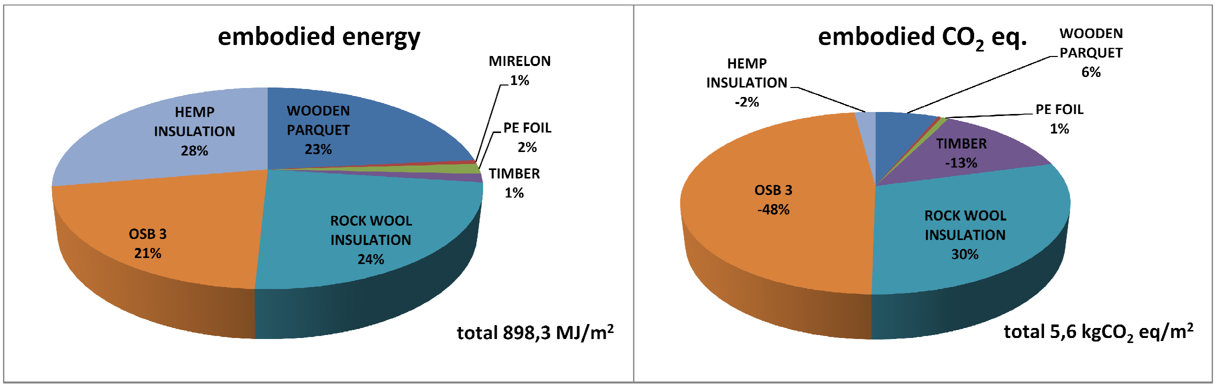
Figure 4. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 1A



(a) (b)

The porous wood fiberboard insulation represents the highest percentage of embodied energy but nevertheless it contributes to reducing of embodied CO_2 eq. emissions. The concrete slab has the most negative impact on carbon balance of this construction alternative because it participates in 46% of production of embodied CO_2 eq. emissions.

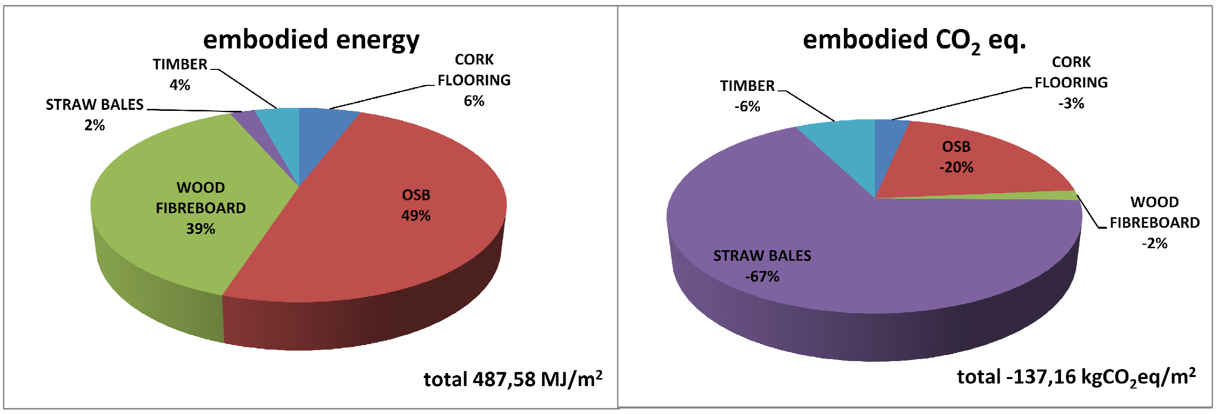
Figure 5. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 1B



(a) (b)

The insulation materials in form rock wool and hemp (in ration of 1 to 3.5) represent the highest percentage of embodied energy. However, the hemp insulation with PE fibers is approximately 60% of the total material composition and contributes only by 28% to total embodied energy, and it participates in reducing of embodied CO_2 eq. emissions. The rock wool insulation is more than 17% of the total material composition, but contributes to considerable production of embodied CO_2 eq. emissions.

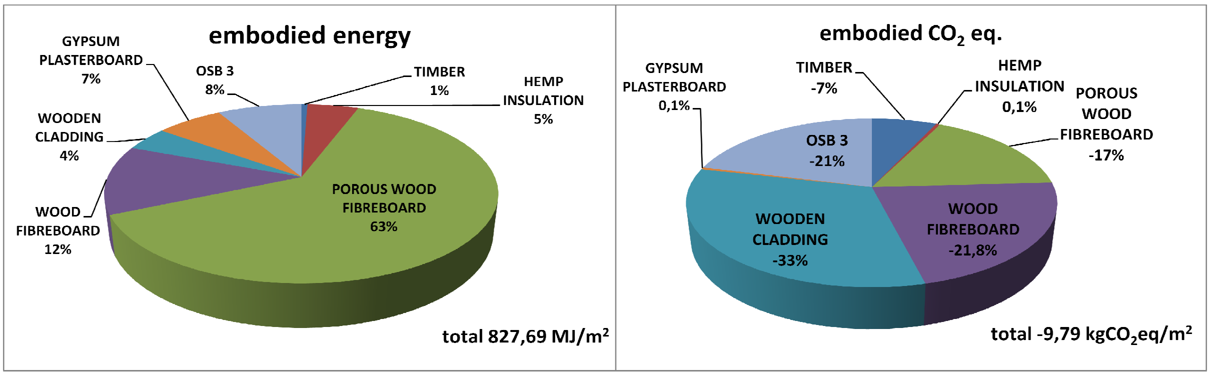
Figure 6. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 1C



(a) (b)

The straw bales as insulation material are approximately 80% of the total material composition and contribute only by 2% to total embodied energy. These bales help in the fight against carbon footprint of construction and participate in 67% of total negative balance of embodied CO_2 eq. emissions. All used materials are on plant base and achieve negative value of CO_2 eq. emissions.

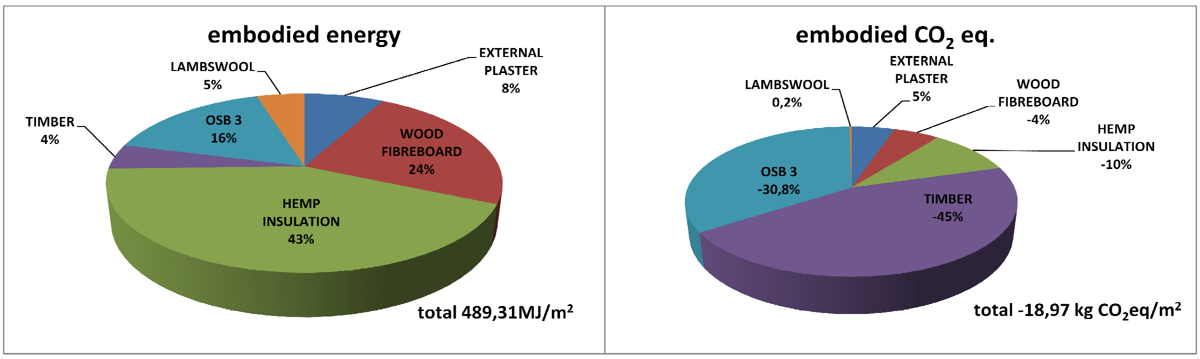
Figure 7. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 2A



(a) (b)

The porous wood fiberboard is main insulation material which is approximately 73% of the total material composition. This material represents the highest percentage of embodied energy (more than 60%) but nevertheless it contributes more than 20% to reducing of embodied CO_2 eq. emissions.

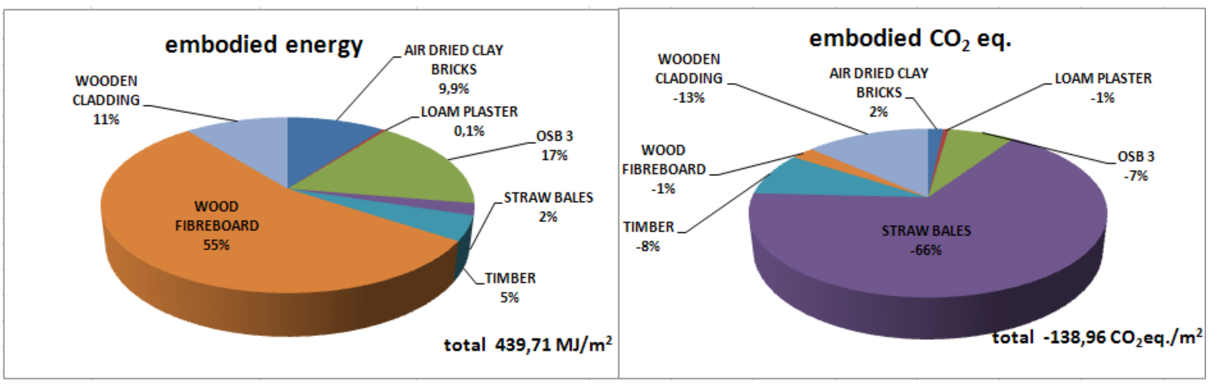
Figure 8. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 2B



(a) (b)

The hemp insulation material represents the highest share of material composition and achieves the highest value of embodied energy, it participates in more than 40% of total embodied energy but nevertheless it contributes to elimination of embodied CO_2 eq. emissions.

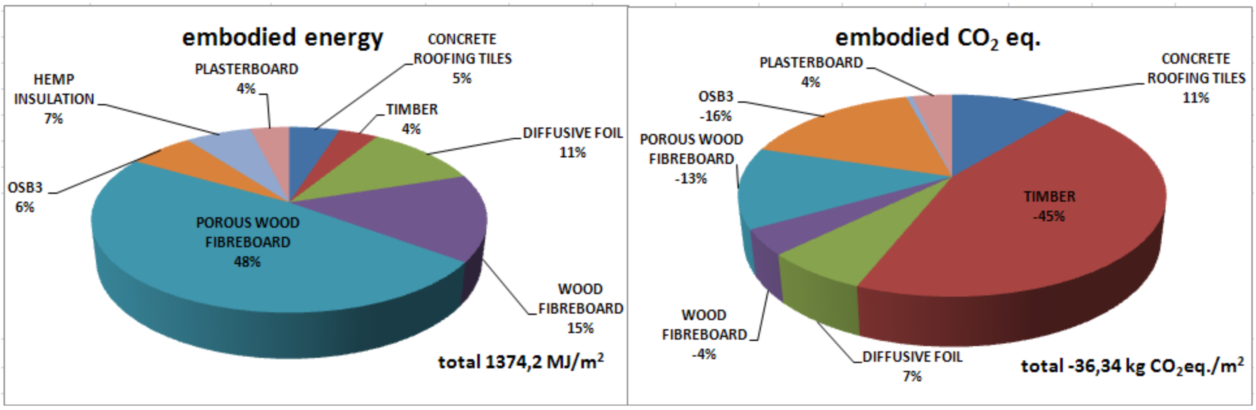
Figure 9. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 2C



(a) (b)

The highest quantity of material composition is calculated for thermal insulation in form straw bales but nevertheless bales contribute by only 2% to the total embodied energy and they markedly improve the total carbon balance.

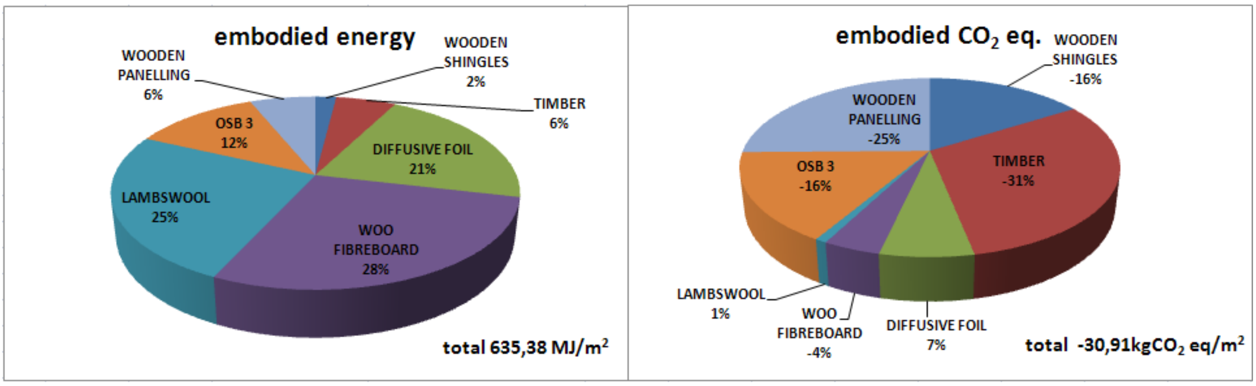
Figure 10. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 3A



(a) (b)

The porous wood fiberboard is main insulation material which represents approximately 65% of total material composition of this construction alternative; it achieves the highest share of total embodied energy but it participates by 13% in negative carbon balance. The timber represents the highest percentage of the total negative embodied CO_2 eq. emissions.

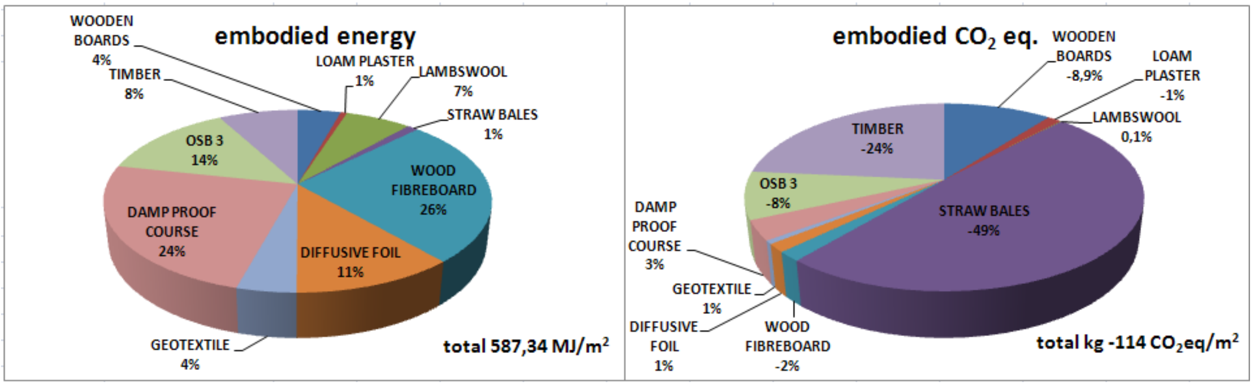
Figure 11. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 3B



(a) (b)

The highest share of material composition is calculated for lambswool. This insulation material is approximately 85% of all used materials for this construction alternative but nevertheless it contributes by only 25% to the total embodied energy. The lambswool is from animal hair and therefore don't achieves negative value of embodied CO_2 eq. emissions but it participates by only 1% in production of CO_2 eq. emissions.

Figure 12. Percentage of (a) embodied energy and (b) embodied CO_2 eq. for alternative 3C



(a) (b)

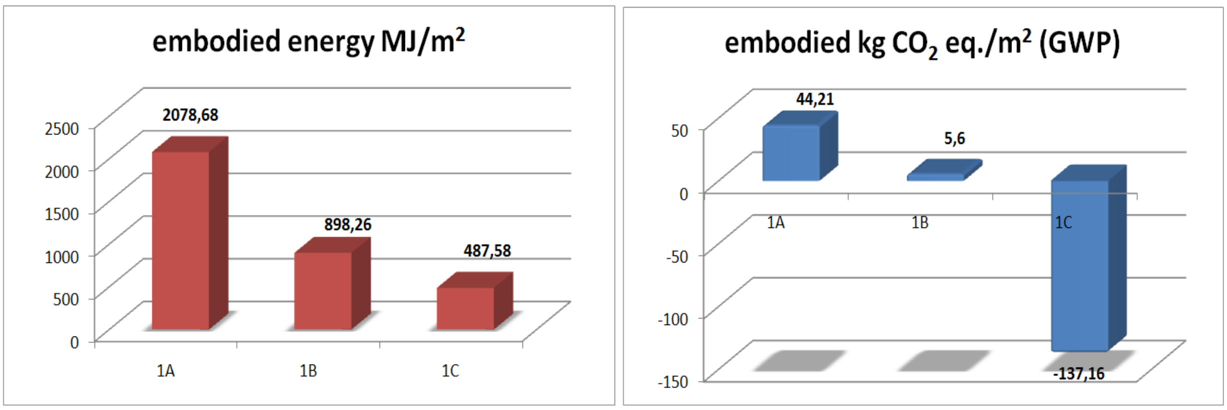
The highest quantity of material composition of this extensive roof construction is calculated for insulation material in form straw bales. These straw bales represent only 1% of the total embodied energy. It contributes the most percentage to elimination of embodied CO_2 eq. emissions.

3. Total Results for Constructions

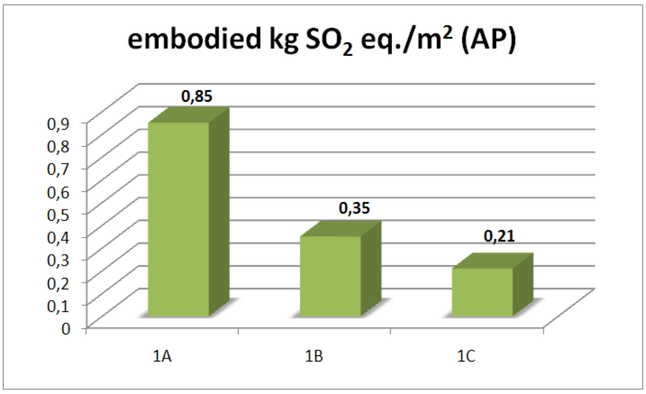
The selection of the building materials of all designed construction variants of wood-framed building induces initial amount of the embodied energy and the emissions which are evaluated by partial LCA analyze. The total results of environmental assessment are seen in following figures 13-15 and prove importance of correct choice of insulation materials.

The particular construction variants are also evaluated in terms of selected thermal-physical parameters. These designed constructions are modeled in software Svoboda- Heat 2009 for climatic conditions of Košice and some parameters are calculated on the basis Slovak valid standard STN 730540. The results are seen in the following tables 2-4. The construction variants were compared in order to assure positive effect on the energy balance of operation of residential building and results in better passive control of summertime overheating.

Figure 13. Resultant values of (a) embodied energy (b) embodied CO_2 eq. (c) embodied SO_2 eq. for floor construction alternatives.



(a) (b)



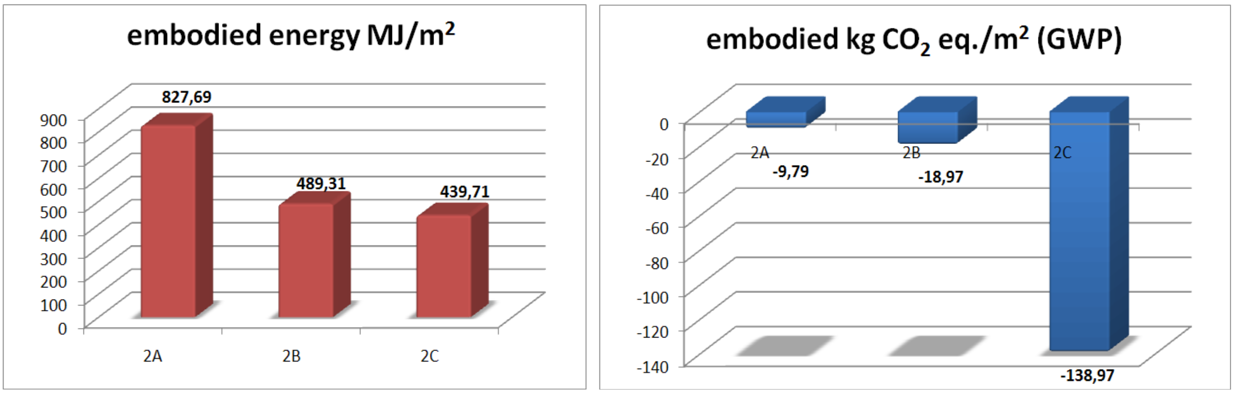
(c)

Table 2. Selected thermal-physical parameters for floor construction alternatives.

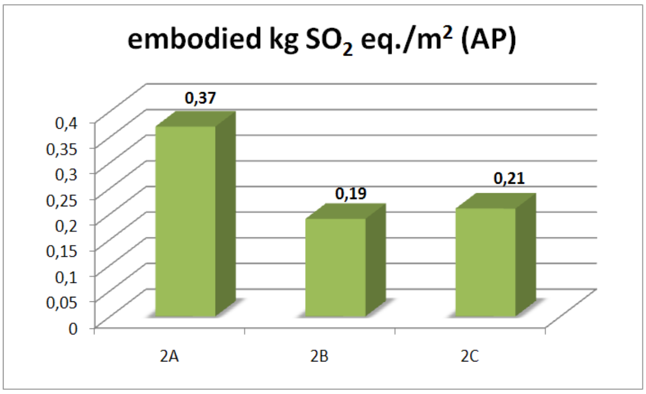
	m [kg/ m^2]	U [W/(m^{2}K)]	Q [kJ]	D [-]
1A	485,77	0,010	579,36	13,37
1B	158,00	0,010	170,85	5,35
1C	96,30	0,091	182,04	11,02

The construction alternative 1C proves the best results from environmental sustainability and demonstrates a possible way to optimization of envelope for green building design. It is about 85% preferable to alternative 1B in terms of embodied energy from non-renewable resources and only this variant is able to absorb a lot of CO_2 eq. emissions and therefore achieves negative carbon balance. The values of heat transmittance (U) prove that floor constructions meet passive energy standard. The construction solution 1C achieves the most convenient value of U, but proves about more than 200% worse value of thermal storage (Q). However, the alternative 1C is the most suitable in terms multi-criteria decision method.

Figure 14. Resultant values of (a) embodied energy (b) embodied CO_2 eq. (c) embodied SO_2 eq. for external wall construction alternatives.



(a) (b)



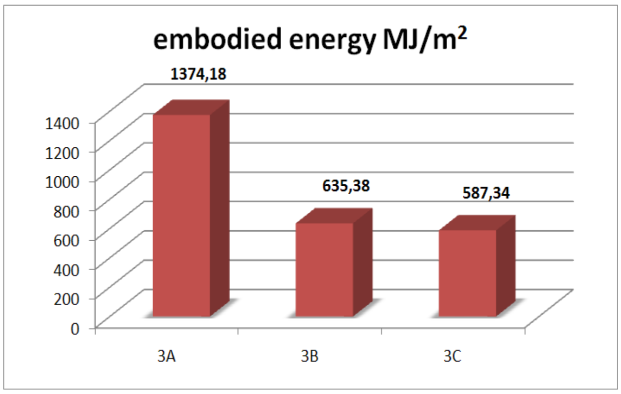
(c)

Table 3. Selected thermal-physical parameters for external wall construction alternatives.

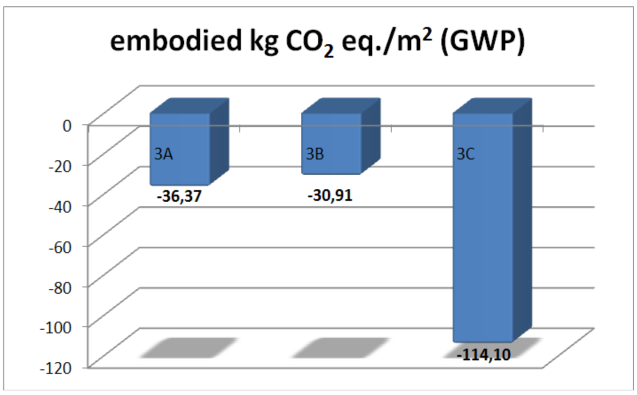
	m [kg/ m^2]	U [W/(m^{2}K)]	Q [kJ]	D [-]	Ψ [hrs]	g_v [kg/m^2.yr]	g_k [kg/m^2.yr]
2A	90,15	0,099	133,41	9,23	24,94	‹0,5	0
2B	40,41	0,102	60,60	4,56	12,30	‹0,5	0
2C	211,20	0,106	263,12	9,03	24,38	8,597	0,010

The construction alternative of external wall 2C is the most sustainable from evaluated alternatives. This variant achieves the best results in terms of Global Warming Potential because participates in reducing of more than 130 kg CO_2 eq. emissions. It is about 11% preferable to alternative 2B in terms of embodied energy and about more than 630% in terms of embodied CO_2 eq. emissions. The alternative 2C achieves the most results considering thermal inertia (D), phase shift of temperature oscillation (Ψ) and thermal storage (Q) and it accounts positive influence on the future operational energy consumption. This variant is also high diffusion opened because it is able to release approximately 8 kg vapor/m^2 per year. The results of environmental and thermal-physical assessments and decision analysis demonstrate that the alternative 2C is the best from long-term point for dwelling.

Figure 15. Resultant values of (a) embodied energy (b) embodied CO_2 eq. (c) embodied SO_2 eq. for roof construction alternatives.



(a)



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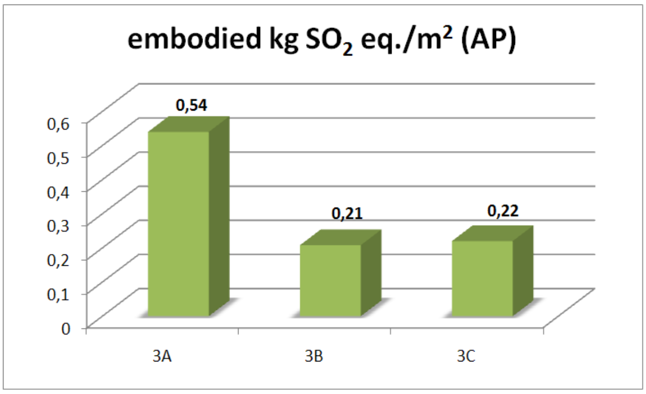


(c)

Table 4. Selected thermal-physical parameters for roof construction alternatives.

	m [kg/ m^2]	U [W/(m^2K)]	Q [kJ]	D [-]	Ψ [hrs]	g_v [kg/m^2.yr]	g_k [kg/m^2.yr]
3A	139,89	0,089	165,25	9,96	26,90	8,432	0,002
3B	65,88	0,087	102,02	5,59	15,09	‹0,5	0
3C	224,08	0,085	192,81	9,47	25,59	3,255	1,264

The alternative of roof construction 3C is the most sustainable from designed alternatives. This alternative of extensive green roof proves the most suitable results of environmental and thermal-physical assessment. It is about more than 8% preferable to alternative 3B in terms of embodied energy and is about 214% preferable to alternative 3A from this point of Global Warming Potential. Thanks its weight achieves the highest value of thermal storage. The resultant values of thermal-physical parameters of alternative 3C contribute to reducing future operational energy consumption.

4. Conclusions

The below optimized construction alternatives 1C, 2C and 3C for envelope of wood-framed residential building are applied in this designed passive house. The bungalow (is seen in Figure 16) is situated in Košice, in Eastern part of Slovakia, the geographic coordinates are 48° 43‘ N latitude and 21°15’E longitude. The Košice belongs to warm climatic zone. The average summer temperature is about 20.5° C and average winter temperature is about -13° C (according to Slovak valid standard STN 73 0540) [19].

The most sustainable alternatives of constructions are mainly from natural environmentally friendly materials such as timber, straw bales, lambswool, cork, loam. These constructions participate in elimination of carbon footprint of whole building, because are able to lock carbon in their mass and therefore achieves the highest negative balance of embodied CO_2 eq. emissions compared with other alternatives. The highest share of environmental performance of house is accounted for insulation material in form straw bales. Used natural building materials improve indoor climate because release no emissions such as VOC, don't destroy important negative ions and can keep positive moisture balance. This green house presents philosophy of healthy housing.

Description of constructions: Foundations consist from reinforced concrete bearer and concrete base foots. Load bearing function fulfills timber frame in form I joists. Thermal-insulating function fulfills: mainly straw bales. Sound-insulating function fulfills: mainly lambswool. Cross walls mostly are made from air dried clay bricks with loam plaster. Surfaces of ceiling are mainly made from natural loam plaster. The final layer of floors is from cork and ceramic tiles. External surface of walls is from larch. Windows and external doors are with triple-glass (filled by argon 2 x 16 mm) and wooden frame with interrupted thermal bridge. Extensive green-roof is designed according alternative 3C.

Figure 16. Scheme of ground-floor of bungalow.

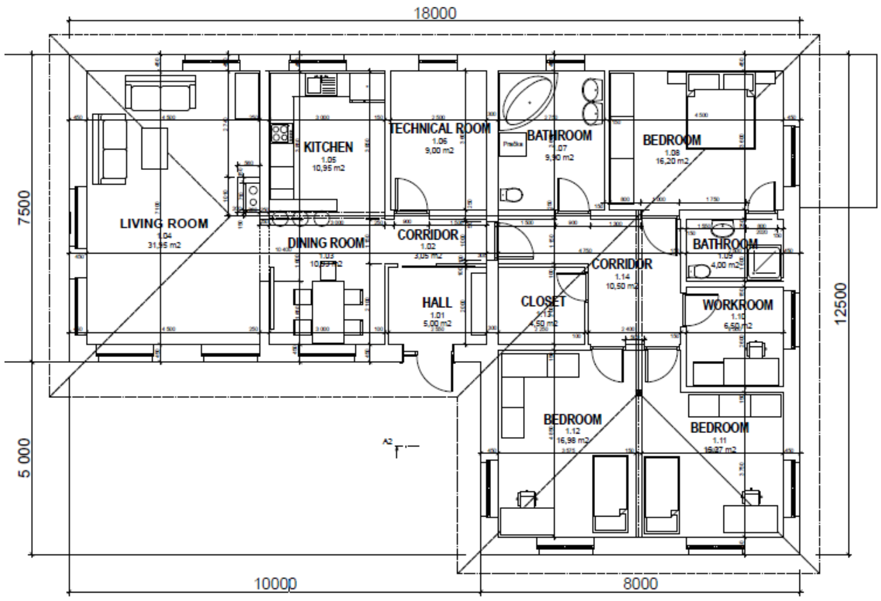
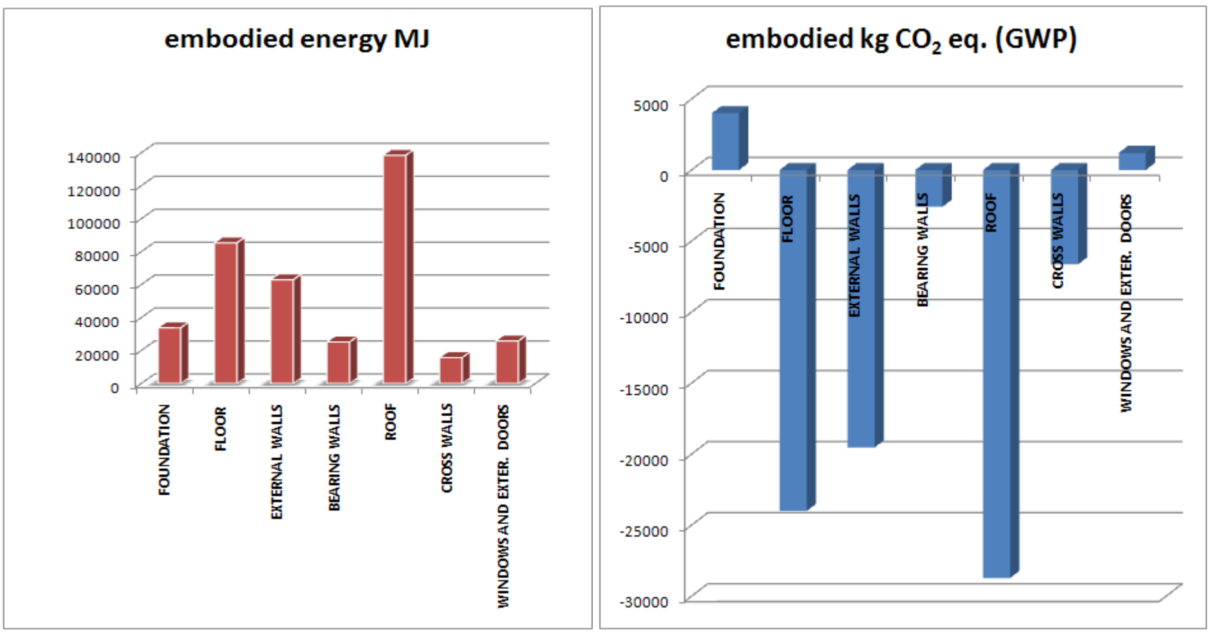


Figure 17. Results of (a) embodied energy and (b) embodied CO_2 eq. emissions for particular constructions of bungalow.



(a) (b)

Table 5. Total results of embodied energy from non-renewable resources and embodied CO_2 eq. emissions for evaluated bungalow.

Total embodied energy MJ	Total embodied kg CO_2 eq. emissions
387 374.489	-76 291.390

The bungalow is designed in view of the concept of sustainable envelope of building which strives to make judicious use of the surrounding resources in order to create a harmonious environment and excellent living space for the dwellers, while minimizing the environmental impacts, and reducing energy consumption in building. Selection of building materials is aimed at maximal using natural, renewable, locally available and recyclable resources. The applied clearly natural plant materials are achieved to store great amount of CO_2 emissions as locked carbon in envelope of house after phase of demolition. This wood-framed house determines reduction of more than 76 ton of CO_2 eq. emissions what corresponds to approximately 550 kg of CO_2 eq. emissions per square meter of its floor area. The evaluated house presents one of the ways of designed green dwelling. The objective of this case study is to develop a framework for modeling the sustainable performance of residential building.

The principle of optimization of material and energy flows within whole life cycle is one of the basic principles of sustainable development. Sustainable or green construction is thus one of the most important challenges we face. And the potential for improvement is huge.

Acknowledgments

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