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Analyzing embodied energy, global warming and acidification potentials of materials in residential buildings

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Abstract

The paper aims at an environmental assessment of twenty residential masonry houses in relation to built-in materials, in terms of embodied energy (PEI), global warming (GWP) and acidification potentials (AP). The overall environmental impacts of houses were calculated based on the unit LCA data of materials considering the masses and volumes of building materials in particular structures. Findings revealed that one conventional masonry house, on average, consumed 310 t of materials. The average of embodied energy (PEI) in one masonry house reached 567.5 GJ while the average global warming (GWP) and acidification potentials (AP) were found as 36.2 t CO_2eq and 0.17 t SO_2eq, respectively. Analysing the environmental impacts of substructures in buildings, materials of foundations were identified to be responsible for the most negative environmental impacts with 29.9 % sharing on the total embodied energy, 57.8 % on the total GWP and 30.4 % on the total AP; followed by thermal insulation, vertical bearing walls and finishing. The summation of foundations and walls materials consumed about 50 % of the total embodied energy. The obtained results could represent the average environmental impacts of residential houses in Central Europe because in the region, masonry dominates as the construction type.

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Keywords: Masonry house; global warming; carbon dioxide; environmental impact; acidification; primary energy

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1. Introduction

Buildings throughout their life cycle contribute to the global environmental problems such as global warming, acidification, raw materials exploitation and energy consumption. Environmental evaluation of buildings and building materials is one of the most significant factors towards on the sustainability in the building industry and built environment.

Application of an environmental assessment in the construction sector is especially not only because of the complexity of the buildings, but also because of their long lifetime. This can cause many difficulties and uncertainties in prediction of the behavior of buildings throughout their life cycle. Life cycle assessment (LCA) is a relatively new method used in construction since 1990. Due to its comprehensiveness, however, it is an important tool for the evaluation of materials, structures and buildings [1,2]. Thus, application the LCA using different boundaries allows to analyze the various systems with different focus and objective. LCA based methods in construction sector are used at three levels: (i) Tools to compare environmental performances (GaBi - Germany, SimaPro - Netherlands TEAM - France), (ii) Tools for evaluation of constructions or particular buildings (LISA - Australia, Ecoquantum - Netherlands, Envest - United Kingdom, Athena - Canada), and (iii) Evaluation tools assessing the whole building systems during their life cycle (BREEAM - United Kingdom, LEED - USA, Grey - Australia, SBToolCZ - CR, BEAS - SR) [1-4]. The evaluation and consequent environmentally-based choice of materials is one of the key factors for minimizing environmental burdens [5]. Databases assessing the life cycle of building materials can be divided into public, academic, commercial and industrial. The data may vary due to different system boundaries, anticipated sources of energy, product specifications and so on. In addition, environmental impacts can be affected also by geographical factors. Selecting the database can therefore affect the reliability of the results of LCA.

Nomenclature

GWP	Global Warming Potential
AP	Acidification Potential
PEI	Primary Energy Intensity, Embodied Energy
LCA	Life Cycle Assessment
OSB	Oriented Strand Board
XPS	Extruded Polystyrene
EPS	Expanded Polystyrene
PVC	Polyvinylchloride

Various LCA studies conducted in recent years included a study of materials in residential buildings [6-11]. Embodied energy, global warming and acidification potentials are of main interest when evaluating the environmental performance of buildings and materials. As for conventional houses, embodied energy of building materials accounted for only 15%, while energy consumption in the operation phase of buildings reached up to 85% [6]. However, considering passive houses, the embodied energy of materials plays much more important role and can account for up to 50 % of the total energy consumption in the building. In the study [7], it was shown that there is a difference between the percentage of embodied energy and the weight of material (e.g. concrete represented 75% of the whole building, while the energy needed for its production represented only 28%). On the other hand, materials used in very small quantities can have a very high negative impact on the environment and therefore need to be included in LCA. As mentioned in [6], despite the fact that plastics represented only 1-2 % of the total building materials, the share on the total embodied energy of building was up to 18-23 %. The most serious impact does not necessarily depend only on the amount of built-up materials and the size of the building, but on the type of materials used. An Italian study focused on flooring materials revealed that marble tiles has been shown to be more environmentally friendly than ceramic ones [12]. González and Navarro [13] estimated that the selection of building materials with low impacts can also reduce global warming potential - CO_2 emissions by up to 30 %. Estokova and Porhincak [14] noted that it is possible to reduce the environmental impacts by up to 61.0 % in particular structures and by up to 10.5 % overall just by a simple change of several building materials in the structures. The importance of integrating recycling into LCA in low energy residential buildings have been investigated in [8,9]. Research showed that 37-42% of the embodied energy in the materials can be recovered through recycling. The study has also highlighted the importance of the choice of materials with a low environmental impact and the need for the application of LCA as a decision support tool already during the pre-construction phase.

The paper is aimed at an environmental assessment of twenty residential masonry houses in relation to built-up materials to calculate the particular environmental impacts of conventional Middle-European houses. The calculated environmental indicators could be deployed in the eco-labelling process for new criteria proposal for masonry houses.

2. Material and methods

2.1. Analyzed buildings

Twenty conventional masonry houses with commonly used building materials have been selected for the environmental analysis. The single-storey and two-storey buildings of various sizes and configurations were characterized by number of inhabitants, floor and volume specifications as reported in Table 1.

Table 1. Parameters of the analyzed buildings.

	Min	Max	Mean	Median
Number of inhabitants	2	8	4	4
Build-up area (m^2)	96.33	296.53	167.62	155.55
Residential area (m^2)	69.44	235.40	151.43	147.82
Floor area (m^2)	62.70	243.09	167.79	166.63
Heated floor area (m^2)	67.20	217.06	151.00	149.49
Built-up volume (m^3)	212.41	682.50	479.73	488.81

Number of inhabitants was an important parameter, which indicated the size of the habited rooms. When calculating the optimal number of inhabitants, the rule of the minimum living space - 8 m^2 and 12 m^2 per one or two persons, respectively, was reflected. Optimal availability, included two adults in the parents' bedroom and one child in every other bedroom, ranged from 2-5 persons with four people, on average, per a family house. Besides number of residents, the floor and volume indicators gave good information about the dimensions of the houses. The floor and volume indicators included built-up area, residential area, floor area, heated floor area, built-up volume.

Built-up area represented a total built-up surface, including a building and objects and structures associated with the building (garage, gutter pavement, terrace, lee, porch etc.). Residential area represented whole usable area, including the floorages of all rooms without walls, a garage, covered and uncovered terraces, balconies etc. Floor area represented the total flooring defined by the external dimensions of building while heated floor area represented only a flooring of heated rooms in the building (stairways, lee, terrace, unheated garages were not included). Built-up volume was calculated as volume of heated rooms based on the external dimensions of the building.

Individual objects differed in amounts and types of materials used. As mentioned above, material composition of objects represented a set of conventional materials commonly used and available in Central Europe and covered a fairly wide range of materials. However, material base of the analyzed houses exhibited similarities, making it ideal for a fairly good comparison between themselves. The materials used in the substructures were relatively uniform and are described in more detail in the following section.

2.2. Methodology of the environmental assessment

The study of the environmental performance of construction materials built in residential buildings was focused on three areas of evaluation: i) overall environmental assessment of the buildings in relation to the built-up materials; ii) assessing the environmental performance of particular structures, and iii) assessing the environmental performance of buildings according to the features of materials.

i) Overall environmental assessment of the buildings in relation to the built-up materials reflected the total amounts of materials in all structures.

ii) Assessing the environmental performance of particular substructures was based on evaluating the groups of materials according to eight groups of substructures as follows:

- foundations,
- vertical bearing walls,
- partition walls,
- horizontal structures - ceilings,
- roofs,
- thermal insulations,
- finishes,
- doors and windows.

All objects were built on shallow foundations represented by strip or raft foundations. Foundation materials included precast concrete strips or reinforced concrete slabs. The bottom of the trenches was filled to grade with gravel, tamping every vertical foot to ensure compaction. Damp proof membranes covering the area of the foundation represented wider range of materials (polymer bitumen sheets, bitumen sheets lined with aluminum foil or plastic PVC).

Vertical load-bearing structures consisted of outer and inner bearing walls. Ceramic perforated bricks were used in twelve buildings whereas eight buildings were built from aerated concrete blocks. Some buildings were also supported by poles (wood, bricks or reinforced concrete). Lintels and interior staircases were made of monolithic - reinforced concrete.

Partition walls were of the identical composition as the load-bearing walls, as confirmed by most of partitions used in the assessed building (ceramic bricks, porous concrete blocks), along with lintels of reinforced concrete. Plasterboard walls on aluminum or wood frames were used only in one building.

Horizontal framework was represented by ceilings. In the analyzed single-storey buildings, ceiling structures were designed as wooden structures. Wood was so often chosen partly because of reducing the material´s weight, but also because the ceilings did not require high strength due to not using attic spaces, in general. In all two-storey buildings, monolithic reinforced concrete ceilings or prefabricated ceilings with application of pre-stressed beams and liners were used. However, the prefabricated panels in the construction of individual houses was used rarely. Reinforcing wreaths were constructed of reinforced concrete.

The roofs of all residential houses were made up of wooden structures represented by wooden framework with one exception, in which wooden trusses were used. An air-dried and technically dried wood and OSB panels were applied in wooden structures. Material of roofing was represented by concrete and ceramic tiles in the greatest extent, as well as aluminum and steel sheets.

Thermal insulation based merely on conventional materials (polystyrene and mineral fibers) were applied in the individual family houses. Extruded polystyrene (XPS) was used in all foundations and most of floor structures. Expanded polystyrene (EPS) had a wider range of applications, such as insulation material in the floors, wreaths, and lintels as well as insulation material in the contact insulation systems of facades. Mineral fibers-based insulation accounted for glass wool (especially in the cavity lining - ceilings, roofs) and stone wool (used in roofs, ceilings, floors and facades). Any alternative natural materials, e.g. cellulose, straw or cotton were not designed in any building.

Finishes of buildings differed depending on the structure where were used. Finishes can be divided into three groups: floor, wall and ceiling finishing. Ceramic tiles, wood flooring, laminate flooring and concrete tiles as treading layer were used in the floors. Various plasters (lime-cement, lime, gypsum, silicate and silicone) and facing materials (ceramic tiles, wood paneling) were applied as exterior and interior walls finishing. Plasterboards with vapor barrier were used in the lower ceiling finishing.

Windows and doors consisted of framework of wood, PVC or combined wood-metal profile and double or triple-pane insulated glass. Inert gases (argon or krypton) were injected between panes of glass.

iii) Assessing the environmental performance of buildings according to the features of materials took into account the classification of built-up materials into the material groups based on the common characteristics of materials as follows: bulk materials (gravel, sand, soil, substrate); concrete materials (precast concrete, reinforced concrete including reinforcement, concrete blocks, tiles, concrete roof tiles aerated concrete blocks); ceramic materials (bricks, blocks, tiles, ceiling panels); wooden materials (wooden poles, roof tiles, flooring, wood-based materials - OSB, fiberboards); laminate (laminate finishes); metals (metal roofing, flashing); mineral thermal insulation (glass wool, rock wool); polystyrene (EPS, XPS); inorganic plastering materials (silicate and silicone plaster, adhesives, facade, lime plaster, cement plaster, plasterboards); organic surface insulation (asphalt strip, foil insulation, vapor barriers, geotextiles); and glass materials (of windows and doors in external walls).

The environmental assessment was based on the calculation the LCA environmental indicators commonly used in construction sector. Apart from the weight and volume, the environmental indicators included:

- embodied energy (PEI),
- global warming potential (GWP), and
- acidification potential (AP).

The weight of materials was calculated on the basis of the material´s inventory, and served not only as one of the endpoints, but as the intermediate stage for the quantification of environmental impacts of other indicators as well. The embodied energy (PEI) is the primary energy from non-renewable sources (oil, gas, coal, nuclear) and it expresses the energy intensity of the manufacturing process within the boundaries of the procedural system. In the true sense it is not a category of impact but the material characteristics, however, in environmental assessments PEI is considered an environmental indicator [15]. Global warming potential (GWP) expresses the greenhouse gases emissions of anthropogenic origin. It can be expressed for different time horizons, usually for 20 to 500 years. In this study, data were used for a period of 100 years [16]. The value of potential is calculated through the amount of primary greenhouse gas - carbon dioxide (kg CO_2eq). Acidification potential (AP) is used to express the contribution of the material to an acidification of the environment. Total acidification potential is expressed in the form of SO_2 emissions (kg SO_2eq).

The environmental indicators (EI) were calculated according to Eq. (1) using the unit LCA values of materials and the total amounts of materials in buildings and substructures, respectively.

$$EI = \sum_i m_i . EI_i \tag{1}$$

where *EI* is an individual environmental indicator (PEI, GWP, AP), m_i is weight of the material in the structure and EI_i is unit LCA indicator of material based on the IBO database [15]. LCA data were based on the cradle-to-gate boundaries (embodied phase), including the energy and greenhouse gases emissions from the materials extraction, transportation, and manufacturing components and products. In addition, the overall environmental indicators were converted to the reference environmental values represented functional units. There are different approaches to define the functional unit in LCA based environmental assessment of residential buildings [17]. In our paper, we converted the calculated environmental parameters to the one square meter of flooring as considered Allacker [18] by dividing the calculated indicators by corresponding floor areas of houses.

3. Results and discussion

3.1. Overall environmental assessment of the buildings in relation to the built-up materials

The embodied energy intensities (PEI), the carbon dioxide equivalent intensities (GWP) and the sulphur dioxide equivalent intensities (AP) arising from associated emissions are given in Table 2 for the analyzed dwellings. To be comparable with the other authors, the functional units defined as indicator per one square meter of flooring are presented as well (Table 2).

Table 2. Calculated environmental parameters of the analyzed buildings.

Environmental indicators	Min	Max	Extent of variation	Average	Standard deviation	Average absolute deviation
Overall						
Weight (t)	150.37	461.64	311.27	310.00	81.56	68.1
Embodied energy PEI (GJ)	233.90	853.56	619.67	567.48	151.89	118.4
Global warming potential GWP (t CO_2eq)	12.51	59.72	47.21	36.19	12.10	9.3
Acidification potential AP (t SO_2eq)	0.071	0.251	0.18	0.169	0.048	0.038
Per one square meter of flooring						
Weight (t/m^2)	1.26	2.85	1.59	1.91	0.44	0.38
Embodied energy PEI (GJ/m^2)	2.50	4.43	1.94	3.45	0.62	0.55
Global warming potential GWP (t CO_2eq/m^2)	0.12	0.38	0.26	0.22	0.06	0.04
Acidification potential AP (kg SO_2eq/m^2)	0.70	1.42	0.72	1.03	0.21	0.18

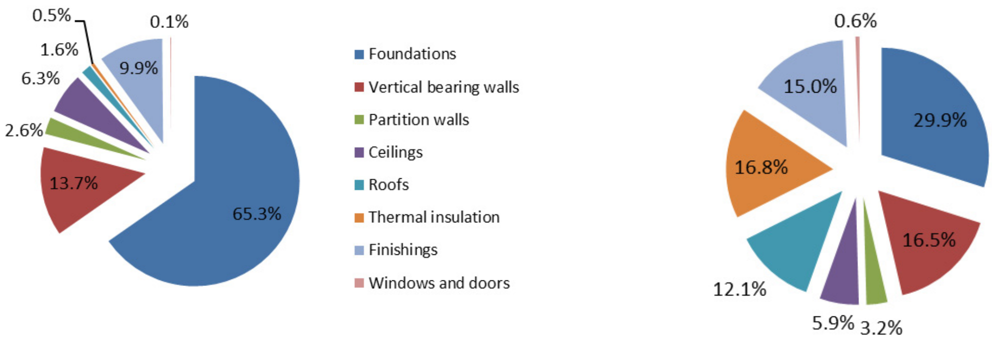
The average overall environmental impacts of buildings reached 567.48 GJ, 36.19 t CO_2eq and 0.169 t SO_2eq for embodied energy, global warming potential and acidification potential, respectively. Findings revealed that embodied energy per one square meter of flooring ranged from 2.5 to 4.43 GJ/m^2 with an average of 3.45 GJ/m^2 which is in accordance with that reported by Abanda for cement-block houses (3.07 GJ/m^2) [19]. On the other hand, Randolph et al. presented much higher embodied energies of 5.4-8.3 GJ/m^2 calculated for residential buildings in Australia [20]. GWP and AP reached 0.22 t CO_2eq/m^2 and 1.03 kg SO_2eq/m^2, respectively. The lifecycle emissions difference between the wood and concrete-framed buildings can vary from 30 to 130 kg per m^2 of flooring as mentioned by Gustavsson [21]. The individual environmental indicators presented by different authors can differ, even for the same functional unit, in dependence on the type and mass of materials used in particular constructions.

These values could represent the average environmental impacts of residential houses in Central Europe because as in most towns and villages in the region, masonry dominates as construction type. Building stock consisted mainly of masonry buildings, mixed types of masonry with timber framework and masonry with reinforced-concrete-frame elements. According to the Statistical Office of the Slovak Republic, between 1990 and 2000, wood and bricks-framed buildings represented only 1.1 and 0.7 % of new-built buildings, respectively. Although, the use of wood-framed buildings increased slightly up to 3.2 % in 2011, the masonry buildings still dominate [22].

3.2. Assessing the environmental performance of particular substructures

Figures 1 and 2 present an average share of materials of substructures on the overall environmental impacts of the residential houses. Materials of foundations were those with the highest weight representing 62.3 % of total weight of materials and have been identified to be responsible for the most negative environmental impacts with 29.9 % sharing on the total embodied energy (PEI), 57.8 % on the total global warming potential (GWP) and 30.4 % on the total acidification potential (AP). The summation of foundation and walls materials consumed about 50 % of the total embodied energy what is in correlation with Kumar who reported 60 % contribution of foundation and walls to the overall embodied energy impact [23]. Monahan showed that timber framing had a lower impact when compared to brick and masonry due to the heavier walls and foundation needed to bear the additional weight, which in turn, increases the minerals required for building construction [24].

Thermal insulation, vertical bearing walls and finishing were also responsible for significantly high negative environmental impacts. The bulk density of thermal insulation (mineral insulation, polystyrene) is relatively low therefore also the weight reached a low measure (0.5 %). However, environmental profile of thermal insulation is significantly more negative and its sharing on the individual environmental indicators was found to be 16.8, 13.3 and 14.6 % for PEI, GWP and AP, respectively. Finishing's materials were found to contribute by 15-20% to the overall environmental impacts. That finding was confirmed by Mithraratne who reported that floor and wall finishes can make



(a) (b)

Fig. 1. Share of materials of substructures (a) on the total weight; (b) on the overall PEI.

(a) (b)

Fig. 2. Share of materials of substructures (a) on the overall GWP; (b) on the overall AP.

up roughly 30% of the embodied phase impact [25]. On the contrary, partition walls structures seem to be those with the lowest impacts in terms of the analyzed environmental parameters as can be observed in Figures 1 and 2. Ceiling and roof structures reached the negative values in global warming potential (GWP) due to application of wood, which is associated with the negative LCA unit data. The negative unit GWP values in the LCA database consider the fact that plants consume the carbon dioxide during their growth.

3.3. Assessing the environmental performance of buildings according to the materials characteristics

Percentage contributions of individual materials groups to the overall environmental impacts of buildings are given in Table 3.

A summary of the quantities of the main materials used for constructing the houses (Table 3) showed that concrete materials accounted for about 43 % of the embodied energy, 50 % of the GWP and 44 % of the AP. This was followed by ceramic materials (21, 14 and 15 %) and mineral thermal insulation with 8, 5 and 10 %. Though polystyrene contributed only 0.1 % by weight, due to its large embodied energy and GWP coefficients, as given in Table 3, its contribution to the total embodied energy and GWP is also relatively large (7.4 and 7 %, respectively). Contribution of wood products to global warming reached the negative level (-17 %), which is a positive fact in terms of carbon dioxide storage. Several materials of the building, specifically, the floors, walls and roofs materials, dominate the impact in the embodied phase according to the study [26].

Table 3. Share of particular materials groups on the overall environmental impacts of masonry houses.

	Weight (%)	Volume (%)	PEI (%)	GWP (%)	AP (%)
Bulk materials	14.8	9.9	0.7	0.3	1.4
Concrete materials	66.4	45.8	42.8	49.7	44.4
Ceramic materials	11.6	17.9	21.1	14.0	15.4
Wooden materials	2.5	5.6	5.5	-17.4	10.1
Laminate	0.1	0.0	1.0	0.2	1.8
Metals	0.1	0.0	1.6	0.9	1.7
Mineral thermal insulation	0.4	11.1	7.5	4.6	9.6
Polystyrene	0.1	6.0	7.4	7.0	5.6
Inorganic plastering materials	3.6	3.1	4.9	3.7	4.6
Organic surface insulation	0.4	0.5	6.9	1.8	4.1
Glass	0.0	0.2	0.7	0.4	1.5

4. Conclusions

The results of the environmental analysis of twenty masonry houses could represent the environmental impacts of residential houses in Central Europe. It can be concluded:

- The overall environmental impacts of a residential house, on average, are represented by 567.48 GJ of embodied energy, 36.19 t CO_2eq embodied carbon dioxide emissions (GWP) and 0.169 t SO_2eq of sulphur dioxide emissions (AP).
- Materials of foundations have been identified to be responsible for the most negative environmental impacts with 29.9 % sharing on the total embodied energy (PEI), 57.8 % on the total global warming potential (GWP) and 30.4 % on the total acidification potential (AP).
- The summation of foundations and walls materials consumed about 50 % of the total embodied energy.
- Thermal insulation, vertical load-bearing walls and finishing contribute significantly to the negative environmental impacts.
- According to the material characteristics, concrete followed by ceramic materials accounted for the highest embodied energy, PEI, GWP and AP.

Based on the findings in the presented study, and based on the fact that masonry buildings dominate in the region of Central Europe, a change in bearing construction materials could lead to a significant decrease in negative environmental impacts of residential houses regarding embodied phase. Although, the operation of buildings is stage with the highest negative impact on the environment in current buildings, in passive houses, also other phases, especially embodied phase, will have to be of an interest. The embodied characteristics of materials will be of greater importance soon since the EU authorities enforce the passive house standards from 2020. The obtained results could be the background for the new environmental criteria design in eco-labelling of the masonry houses.

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