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Environmental analysis of residential exterior wall construction in temperate climate

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Keywords: enclosing structures, global warming potential, production of building materials, greenhouse gas emissions, life cycle assessment, heat-losses, insulating materials, thermal transmittance

Abstract. With the growth of the construction industry market there is an urgent need to evaluate the use of building materials from the sustainable point of view. Product stage of construction materials has a significant negative impact on the environment. This work represents environmental assessment of the construction materials of a low-rise residential building located in the temperate climate zone. To conduct such an analysis, we used a comprehensive methodology, product life cycle assessment (LCA), complying with international standards ISO 14044 and ISO 14025. The global warming potentials were calculated for the building life cycle product stages (A1-A3) in the equivalent of the carbon dioxide emissions (CO_2e). It was found that external walls have the greatest negative impact on the environment compared to other building elements. Production of construction materials for external wall structures is responsible for 45 % of the total CO_2e emissions. Based on the performed calculations, alternative options for exterior wall construction are proposed. Heat losses were calculated for each type of enclosing structures, as well as greenhouse gas emissions from burning fuel for heating the building. It was found that an aerated concrete wall with ventilated facade has the least negative impact on the environment, even though heating a building with such an enclosing structure requires more energy than other wall options. Environmentally reasonable approach of the enclosing structure selection allowed a reduction of greenhouse gas emission by 16.7 %, from 402.85 tons to 335.65 tons CO_2e.

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1. Introduction

Climate change is one of the leading problems in the global community today. The specificity of the problem of global warming lies in the irreversibility of the consequences caused by the widespread emission of greenhouse gases, as well as in the direct impact on all spheres of human life. The climate map of the world for the periods 1980–2016 and 2071–2100 clearly shows cardinal climate changes due to global warming in different regions of the earth [1].

The development of clean energy technologies and the problem of climate change occupy one of the central places in the modern international economic agenda. The key achievement of recent years has been the conclusion of the Paris Agreement in 2015 under the auspices of the UN Framework Convention on Climate Change (COP-21). The energy transition taking place at the present stage involves the active introduction of low-carbon energy sources [2]. The European climate legislation, numbering dozens of directives, norms, and decisions, regulates the entire spectrum of the climate, energy, and economic agenda [3].

According to [4], the industrial sector's contribution to the global Warming Potential (GWP – Global Warming Potential) was 21 % in 2010. Urban population growth requires a constant increase in residential buildings and the construction of urban infrastructure. If the world's population increases to 9.3 billion people by 2050, then there will be a need to develop urban infrastructure. However, the production of building materials for this infrastructure alone, using technologies available today, will lead to greenhouse gas emissions of approximately 470 Gt CO_2 eq. According to the UN, the world's population has already surpassed the mark of 8 billion people [5] as of November 2022.

Life Cycle Assessment (LCA) of buildings and structures makes it possible to assess the contribution of construction industry to the Global warming by calculating greenhouse gas emissions, energy consumed and other parameters at various stages of construction. These stages include materials production, their transportation to the construction site, building demolition and waste recycling [6, 7]. The LCA data of buildings show that 70–80 % of all greenhouse gas emissions occur precisely at the stage of materials production. According to [8], buildings are responsible for 40% of energy consumption, and for 36 % of greenhouse gas emissions throughout the EU.

LCA of building materials is part of the Environmental Product Declaration (EPD) and comply with EN 15804+A21 and ISO 14025 standards (Fig. 1). The presence of EPD for a particular product is a convenient tool that allows you to compare analogous materials on their impact on the environment and choose the best option from it.

LCA stages A1-A3 are responsible for the largest share of energy consumed and greenhouse gas emissions in construction, reflect the impact of processing of natural raw materials, its transportation, and production of building materials.

Product stage			Construction process stage		Use stage							End of life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Opertaional water use	Demolition	Transport	Waste processing	Disposal	Reuse - Recovery-Recycling Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 1. LCA of building materials, stages.

Use phase of building also impacts environment during the life cycle. For example, building orientation (rational use of solar radiation), building configuration (reducing the area of external enclosing structures by combining several residential buildings in-to a block [9]), use of energy-efficient engineering systems, service life of enclosing structures and building retrofitting measures [10–13].

The market provides a variety of building materials [14] with different compositions, physical properties obtained through the use of various production technologies. There is an urgent need to evaluate the use of building materials from the sustainable point of view. Preference should be given to materials with minimal GHG emissions, minimal energy costs and minimal waste during production, as well as optimization of solutions in accordance with today's environmental agenda. Furthermore, the construction industry must minimize the consumption of both embodied and operational energies to achieve a sustainable built environment [15–16].

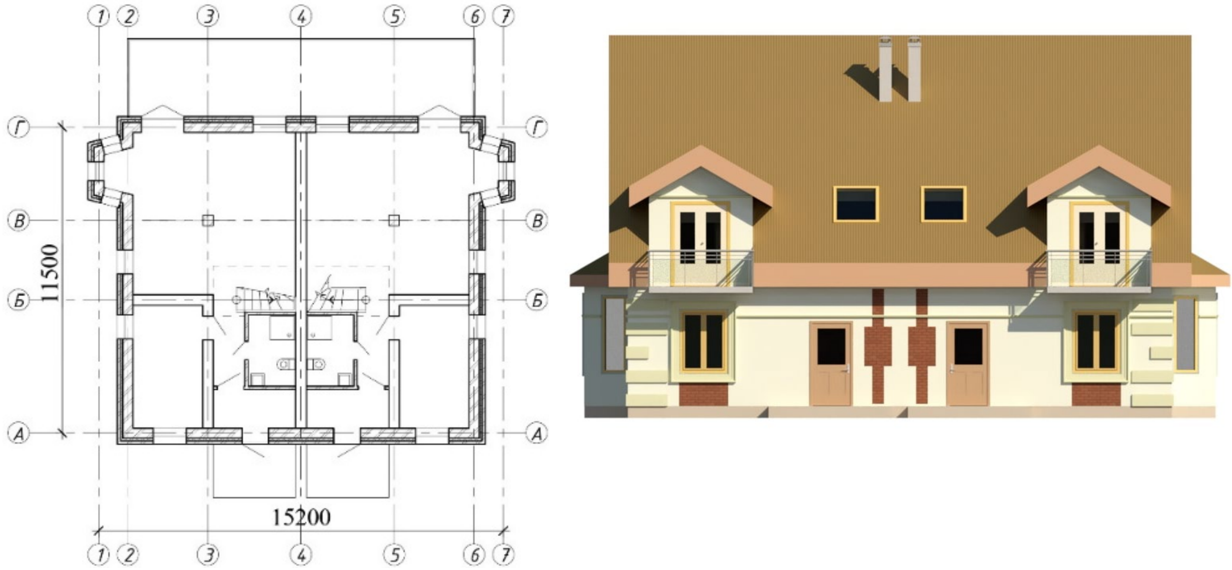
The purpose of this study is an environmental assessment of the construction materials of a low-rise residential building. This goal was reached through the following steps:

1. Design of a low-rise residential building considering materials selection;
2. LCA of building materials (stages A1-A3);
3. Analysis of LCA results, conclusions and design optimization;
4. Calculation of heat losses and greenhouse gas emissions for building heating.

Results analysis provides an opportunity to optimize accepted decisions and reduces the negative impact of construction on the environment.

2. Materials and Methods

The object of the study is a two-storey blocked residential building (Fig. 2) with a living area of 261 m^2. The dimensions of the building are 11.5x15.2 m. Enclosing structures and reinforced concrete columns are loadbearing structures. Internal walls are made of aerated concrete.



(a) **(b)**

Figure 2. Two-storey residential house: (a) Building plan; (b) Building facade.

The building is located in the temperate climate zone (St. Petersburg, Russia). The thickness and composition of the enclosing structures of the walls, roof and foundation were determined in accordance with local requirements. The building materials used as part of various structures are presented in Table 1, where the mass and volume of materials are indicated. LCA results of used materials allow us to estimate the contribution of each of them to the total amount of greenhouse gas emissions from construction. One Click LCA software was used to calculate the amount of greenhouse gas emissions at stages A1-A3 of the materials life cycle, which is also shown in Table 1. The software is compliant with EN 15978 standard and followed by Environmental Product Declarations (EPDs) based on the ISO 14044 and EN 15804 standards.

Materials shown in Table 1 were quantified by using a 3D model of the object. The aforementioned software allows the user to specify the materials applied in the project and assign manufacturers to existing materials. One Click LCA[1] can assess the potential environmental impacts associated with product quantifying lifetime environmental impacts. The program uses the following information, such as material quantity and its environmental performance derived from EPD of each material or generic database. All materials are divided into structures in which they were considered during the project design, making it possible to divide total building emissions into structure groups. LCA assesses several environmental impact categories, with Global Warming Potential (GWP) being the most widely recognized. Table 1 shows the assessment result of carbon footprint from the material product stage (A1-A3).

Table 1. Building materials.

Material	Weight, ton	Volume, m^3	Emission, ton of CO_2e, (stage A1-A3)
1. Foundation – 44.76 t CO_2e ~ 13 %			
Sand	43.93	26.12	0.1
Extruded polystyrene	0.55	17.42	9.65
Sawn timber	1.82	1.74	1.56
Reinforced concrete	108.85	43.54	33.2
Geotextile	0.063	0.17	0.25

[1] URL: https://www.oneclicklca.com

Material	Weight, ton	Volume, m^3	Emission, ton of CO_2e, (stage A1-A3)
2. Vertical structures – 214.2 t CO_2e ~ 63 %			
External load-bearing walls			
Stone wool	2.25	22.5	4.6
Bricks	176	110	149
Columns			
Reinforced concrete	13.5	5.4	2.5
Internal walls			
Aerated concrete	26.77	53.54	28.2
Bricks	35.2	22	29.9
Gypsum	0.2	0.24	0.02
3. Horizontal structures – 75.7 t CO_2e ~ 23 %			
Floor slab			
Reinforced concrete	61.025	24.41	18.6
Gypsum	2.6	3.5	0.76
Extruded polystyrene	0.44	14	7.76
Sawn timber	1.47	1.41	0.91
Vapour barrier	0.02	0.03	0.84
Roof			
Gypsum	5.3	7.13	1.54
Sawn timber	16	35.54	11.2
Extruded polystyrene	0.45	14.2	7.86
Stone wool	4.27	42.67	8.62
Shingles	12.5	3.41	14.5
Waterproofing membrane	0.66	0.43	1.4
Vapour barrier	0.04	0.06	1.7
4. Doors & windows – 3.4 t CO_2e ~ 1 %			
Sawn timber	2	4.4	1.51
Glass	0.89	0.4	1.91
	Total:		339

3. Results and Discussion

The total contribution of each type of construction to greenhouse gas emissions is shown in Fig. 3.

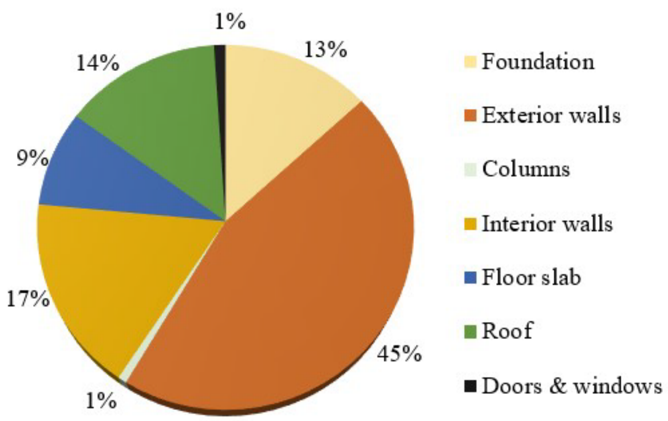


Figure 3. Building structures contribution to the total greenhouse gas emissions.

The greatest impact of material production on the carbon footprint is exerted by materials of the exterior walls (45 %). Fig. 4 shows the composition of the initial structure of the three-layer external wall of the considered residential building.

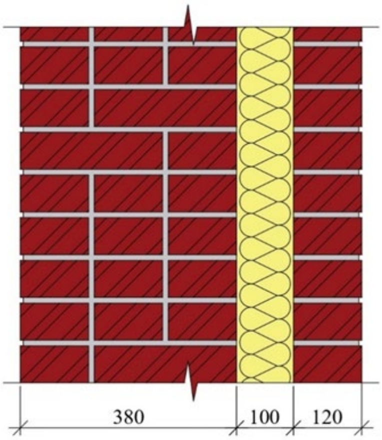


Figure 4. Exterior wall I, U_I = 0.28 W/(m2 · K).

Assessment results of the contribution of each material to the total greenhouse gas emissions at the A1-A3 LCA stages (Fig. 5) show that bricks, mainly as part of exterior walls, are responsible for 53 % of greenhouse gas emissions. Therefore, in order to reduce the initial value of emissions, first of all it is necessary to optimize the design of external walls by changing its composition so that its properties meet the requirements for thermal protection for the relevant construction region [17–19].

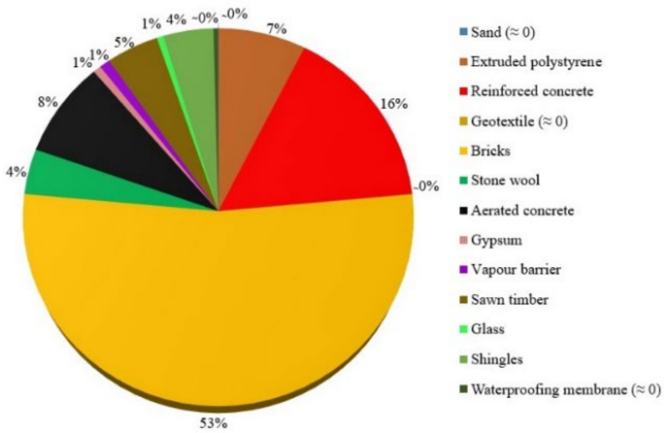
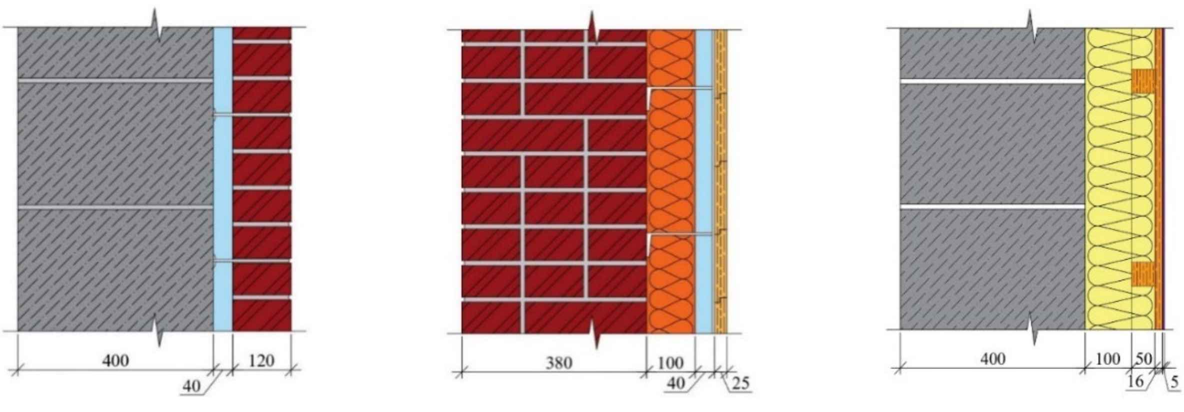


Figure 5. Materials contribution to the total greenhouse gas emissions.

The purpose of the environmental assessment is mainly the choice optimization of building materials based on the LCA analysis results. Alternative designs of exterior walls, which are shown in Fig. 6, were chosen based on their popularity among private residential construction.



(a) **(b)** **(c)**

Figure 6. Types of exterior walls: (a) Type II, U_{II} = 0.29 W/(m² · K); (b) Type III, U_{III} = 0.27 W/ (m² · K); (c) Type IV, U_{IV} = 0,13 W/ (m² · K).

CO_2 emissions from the production of 4 different types of enclosing structures are shown in Table 4. According to the calculations, the exterior walls II-IV are the most environmentally friendly compared to the original version. All walls meet the requirements for thermal transmittance. It can be concluded that the exterior wall IV is the most optimal choice for the construction of a two-storey residential building.

Table 2. Exterior walls constructions comparison.

№	Material	Thickness, m	U-value, W/ ($m^2 \cdot K$)	Emission, ton of CO_2e (stage A1-A3)	Construction contribution to total greenhouse gas emissions, %	Total emissions from materials, ton of CO_2e (stage A1-A3)
I	Solid brick M150	0.38	0.28	153.6	45	339
	Stone wool	0.10				
	Hollow brick M150	0.12				
II	Aerated concrete D500, B3,5	0.40	0.29	83.7	31	270
	Air layer	0.04				
	Hollow brick M150	0.12				
III	Solid brick M150	0.38	0.27	130.4	41	318
	Extruded polystyrene	0.10				
	Air layer	0.04				
	Sawn timber	0.025				
IV	Aerated concrete D500, B3,5	0.40	0.13	59,5	24	244
	Stone wool	0.1				
	Stone wool	0.05				
	Oriented strand boards (OSB) panels	0.016				
	Façade tiles	0.005				

The heat loss of the building through the enclosing structures is calculated to determine the amount of heat needed for building heating. The calculation was carried out only for external walls in order to select the most effective design. The amount of heat lost by the building through the enclosing structures of the exterior walls is determined by the formula (1):

$$Q = S \cdot \Delta t \cdot T \cdot U, \tag{1}$$

where S is wall area, [m^2], Δt is temperature difference, [K], T is heating period, [h], U is thermal transmittance of the wall, [W/($m^2 \cdot K$)].

The area of the facade remains unchanged for each type of structure and it is equal to 225 m^2. The following values were taking for the calculation based on local climate data and technical standards [20]: external temperature is (–24 °C); internal temperature is (+18 °C); heating period is 224 days.

Thermal transmittance was calculated earlier and given in Table 2. It is considered that 1 kW = 1 kJ/s, 1 kWh = 3600 kJ, and 1 Gcal = 1163 kWh. It is necessary to know the calorific value of natural gas, the density and the amount of emissions per 1 kg of used natural gas in order to calculate the amount of greenhouse gas emissions. Natural gas was chosen as the most widely used type of fuel for building heating in Russia. The calculation is made in tabular form (Table 3).

Table 3. Calculation of heat losses and greenhouse gas emissions.

Parameter	External wall I	External wall II	External wall III	External wall IV
U-value of the wall, W/(m^2·K)	0.28	0.29	0.27	0,13
Facade area, m^2	225	225	225	225
Temperature difference, K	42	42	42	42
Heating season, h	5064	5064	5064	5064
Heat loss through external walls, W·h	13399344	13877892	12920796	6221124
Heat loss through external walls, MJ	48238	49960	46515	22396
Calorific capacity of natural gas for 1 MJ/m^3	33.5	33.5	33.5	33.5
Natural gas consumption per year, m^3	1439.9	1491.3	1388.5	668.5
Natural gas density, kg/m^3	0.68	0.68	0.68	0.68
Mass of consumed natural gas, kg	979.1	1014.1	944.2	454.58
Greenhouse gas emissions, kg CO_2e per 1 kg of consumed gas	2.64	2.64	2.64	2.64
Total greenhouse gas emissions, kg CO_2e per year	2585	2677	2493	1200
Heat loss through external walls, Gcal	11.53	11.94	11.12	5.35

Let us assume that service life of the building is 50 years and calculate the total CO_2 emissions (Table 4):

Table 4. Total calculation of CO_2 emission.

Wall type	External wall I	External wall II	External wall III	External wall IV
CO_2e emission from the materials production, ton	339	270	318	244
CO_2e emission from burning fuel for building heating, ton	129.25	133.85	124.65	60
Total CO_2e emission, ton	468.25	403.85	442.65	304

4. Conclusions

It follows from the calculation results (Table 3) that the most environmentally friendly and cost-effective option in operation is the external wall IV. Low U-value of this wall type makes the mass of consumed fuel several times less than value of fuel consumption in other cases. It is important to note that wall structures with that low U-value are rarely applied in given region because construction standards in Russia do not require such a low value of thermal transmittance of external walls (U-value of 0.2–0.3 is sufficient to meet existing requirements). Considering the data in Table 2, which shows the results of calculating the amount of greenhouse gas emissions during material product stage, the most environmentally friendly option also is external wall IV. It can be explained that prevailing material used in producing this type of external wall (aerated concrete) has low CO_2 emission per unit of mass. Moreover, this type of external wall does not have brick in its composition, which has the greatest amount CO_2 emission per unit of mass.

Operation stage of the building (building heating) does not cause such harm to the environment as the production of building materials despite the fact that calculations were carried out for the service life of

50 years. According to the results in Table 4, CO_2 emissions from building heating do not exceed 1/3 of the total CO_2 emissions. Furthermore, the lower the U-value is, the smaller this ratio is.

The possibilities of optimization, such as the number of alternative options of certain structures as well as the number of materials suitable for use, have their strict limits in each specific situation, depending on the type of building being designed, its features, dimensions, requirements for strength, stability and rigidity of load-bearing structures, thermal protection of enclosing structures, etc. [21]. The calculations carried out in this study are an example of the fact that the choice of building materials should be comprehensive. It means that it is necessary to consider the criterion of environmental friendliness, which has a direct impact on the environment, in addition to the standard criteria.

In many ways, a similar assessment of the building materials of a residential low-rise building was carried out in the study [20]. As a result, materials that have the greatest contribution to the total amount of greenhouse gases from the construction of the building (at A1-A3 stages of LCA) are concrete and wood as part of the foundation structures, ceilings and exterior walls. Also, in cases [22–24], it was found that concrete is the most dangerous in terms of its contribution to the total amount of greenhouse gases. In the study [25], ceramic bricks make the greatest contribution to the total amount of emissions. The assessment of the life cycle of an industrial building [26] shows that in buildings of this type, concrete (reinforced concrete) is the material responsible for the largest percentage of greenhouse gas emissions, due to massive load-bearing reinforced concrete structures.

Thus, based on the results of this study, confirmed by other works, we can conclude that the most popular building materials, such as concrete and brick, which are used everywhere, are the reason for the large GWP in the construction industry. According to [27], in terms of the amount of greenhouse gas emissions and the amount of energy consumption, the use of a wooden frame is the best option for the construction of low-rise residential buildings. However, replacing concrete and brick with wood is not always possible. Therefore, it is worth paying attention to manufacturers of building materials and their environmental product declarations (EPD). Emissions from the same material but from different manufacturers may differ by several times.

This work evaluated the product stages of building LCA (A1-A3). In further studies, it is planned to evaluate the construction stage (transportation to construction site A4 and installation A5).

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