WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.155083

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 3 2025

pp. 11 –31

Research paper

Ecological life cycle analysis (LCA) on the example of materials used in warehouse buildings

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Abstract: Construction cannot be called as an environment friendly process, hence many solutions are being developed to define the negative interactions of the buildings, determine the extent of environmental impact and find alternatives to improve design performance. The paper examines environment impacts of two warehouses using LCA methodology that has been widely applied in the construction sector, since 1990, taking into consideration life cycle stages from cradle to grave with separate summary for product stage, construction process, use stage and end of life. Phase of the building operational energy use is not discussed in the article. Paper focuses on evaluation of building materials instead of operations of facilities. Analysis takes into account following environment impacts: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Photochemical Ozone Formation Potential (POFP) and Non-Hazardous Waste Disposed (NHWD). The main conclusion derived from the received results of the warehouse buildings case study is that the product stage is a particularly important phase of the life cycle, as it reveals the highest levels of emissivity impacts among the analyzed stages. The paper indicates materials that are responsible for the greatest impacts.

Keywords: ecological life cycle analysis (LCA), LCA stages, environment impact, GWP, construction materials, warehouse

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1. Introduction

The assessment of the impact of the construction sector on the environment, carried out on a micro, meso or macro scale, is gaining more and more importance, because the existing relations between the economy and the environment consisting of extracting and processing natural resources and discharging pollutants and waste into the environment caused its degradation, posing a threat to the further development of civilization. Thanks to the development of appropriate methods and tools, decision-makers can obtain information on the flow of harmful substances in the environment and analyse specific environmental problems, such as global warming, in terms of the entire economy or individual components. The information obtained supports decision-making processes. Considerations about the impact of construction on the environment can be considered on the meso scale (local building materials market, housing estate, city), macro (the entire construction sector, state territory) and on the micro level (single building material, component, building, single supplier).

The genesis of the first studies on environmental impact took place in the 60s and 70s [1]. A useful tool to support the ongoing assessment of decisions made in this area is the LCA (Life Cycle Assessment) methodology, which has become a recognized and recommended method of assessing pro-ecological projects. Although the general basis for the energy and ecological analysis of the full life cycle of products was developed at the end of the last century, the interest in it is growing and it is constantly being improved. An attempt to standardize and harmonize the methodology resulted in ISO 14040 standard published in 1997 [2]. Further development allowed to distinguish 3 types of LCA approaches Process-Based, Economic Input-Output (EIO), and Hybrid [3, 4] that are often applied by researchers in their field of research.

The aim of this article is a multidimensional ecological analysis covering a number of environmental impacts, including: global warming potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical ozone formation potential, non-hazardous waste disposal. Following the worldwide climate strategies preventing global warming and new restrictions constantly being developed the paper presents the fraction of indicated problem of climate contamination range by revealing the scope of emissions connected with the warehouse design that recently is growing especially in Poland where the analysis is undertaken. The article examines the environmental impact of warehouse buildings in the entire life cycle in a cradle-to-grave approach. The influence of the impacts at individual life cycle stages was analysed and the potential benefits and loads were taken into account. The attempt of carbon footprint calculation becomes everyday life. It is very reasonable behaviour, however not only the reference value which is CO_2 is responsible for unwilling climate changes. Ecological considerations in the long run shouldn't neglect other factors impact. The calculations take into account the share of selected impacts depending on the life cycle stage and certain material influence in order to indicate some differences between impacts. It allows to remark especially significant differences in materials emissions depending on the material used. The results encourage further consideration of solutions with the least possible impact on the environment. The discussion of the results obtained as part of the LCA analysis covers the division of buildings into elements grouped, i.e. structural frame, envelope, substructure, roof, interiors and openings, and includes the perspective of the division of buildings by material groups e.g. steel, ready mix concrete, precast.

2. The importance of ecological assessment – a literature review

2.1. Background

Contemporary society strongly follows the idea of sustainable development in order to counteract the consequences of global decisions that led to environment deterioration. This idea is based on three pillars that are inseparable: environment protection, economic efficiency and social balance. Environmental issues are an inseparable element of public debate since the industrial revolution. Continually new steps and policies are undertaken all over the world to introduce and promote ecologically sustainable development. In 2015, the Paris Agreement brought the first, common, legally binding agreement of almost 200 countries in the field of climate. A worldwide action plan was presented, which was aimed at preventing climate change, due to the limitation of global warming to a value far below 2°C. In the end of 2019, the European Commission introduced policy initiative called "European Green Deal" that proposed further goals for reducing greenhouse gas emissions by 2030. Established goals assumed minimum 55% cuts in greenhouse gas emissions, above 32% share of renewable energy, and at least 32.5% improvement in energy efficiency. Reduction of emissions by 2030 is compared to the amount calculated for the base year (base year is established in 1990). The Commission also proposes that all new buildings must be zero-emission by 2030. Furthermore, all new public buildings must become zero-emission by 2027. This means that buildings should consume small amount of energy, be powered by renewable solutions as far as it is possible, emit no on-site carbon emissions from fossil fuels and must indicate their global warming potential based on their whole-life cycle emissions on their Energy Performance Certificate.

Looking to the future all 27 European Member States agreed to undertake steps to transform EU into the first climate neutral continent by 2050. It is associated with many initiatives that should bring greenhouse gas emissions to net zero. Limited time and willingness to meet the conditions of Paris Agreement determines accelerated actions to transition to a low-carbon economy (also referred to as a decarbonised economy) – economy based on low energy consumption and low pollution. "The low-carbon economy can be seen as a step in the process towards a zero-carbon economy" [5]. This is definitely quite a serious challenge looking at recent global average levels of CO_2 trend monitored by NOAA Global Monitoring Laboratory (Fig. 1).

Undoubtedly, construction cannot be called as an environment friendly process, hence many solutions are being developed to define the negative interactions of the buildings, determine the extent of environmental impact and find alternatives to improve design performance. Buildings have an impact on the environment throughout whole life starting with extraction of material, construction, maintenance till the end e.g. withdrawal or replacement.

The idea of environment friendly construction processes is not a recent term because the first steps in this direction were taken already in the 1970s as a result of oil crisis. At the time "saving energy in the construction and operation of building has been a strategic issue in the building industry" [6]. However, since then, the implementation of environment friendly technologies and the deepening of ecological awareness of the society have led to the development of methodologies and tools enabling making conscious decisions concerning building constructing/demolition processes, at all implementation phases.

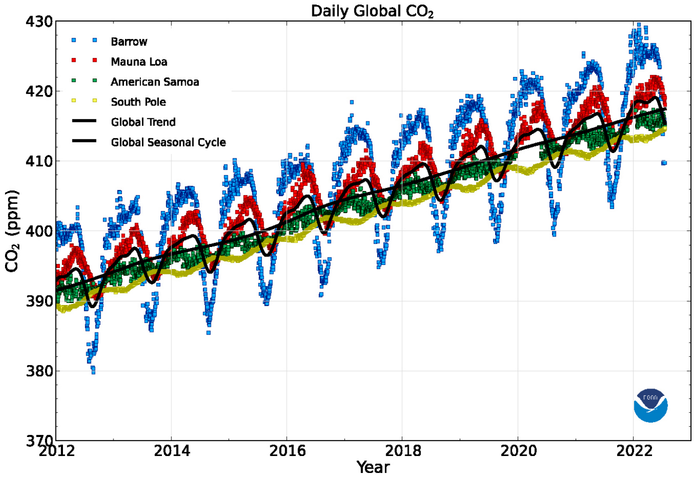

Fig. 1. Recent Global CO_2 Trend. Colours represent daily averaged CO_2 from four observatories: blue – Barrow, Alaska, red – Mauna Loa, Hawaii, green – American Samoa, yellow – South Pole, Antarctica. Thick black curves represent Seasonal Cycle and Global Trend (source: National Oceanic & Atmospheric Administration, Earth System Research Laboratories Global Monitoring Laboratory, https://gml.noaa.gov/ccgg/trends/gl_trend.html; access: 21.07.2022)

Furthermore, care for the environment should be consistent with finance aspects, which undoubtedly affect decision-making process. Scientists are constantly trying to find optimal solutions to reach compromise between GHG emissions and costs throughout the whole life cycle of a construction investments [7–9]. Each new study published provides valuable insights that contribute to the goal of climate neutrality by 2050.

2.2. Life Cycle Assessment

This paper will examine environment impacts of products using LCA methodology that has been widely applied in the construction sector, since 1990, as an important tool to evaluate the environmental impacts of building materials over the different life cycle phases of the construction project [10], taking into consideration life cycle stages from cradle to grave with separate summary for product stage, construction process, use stage and end of life. Phase of the building operational energy use is not discussed in the article. Paper focuses on evaluation of building materials instead of operations of facilities. Applied methodology (LCA), based on ISO 14040, comprises four steps: the goal and scope definition, inventory analysis, impact assessment and interpretation of the results [11]. "LCA is defined as a systematic, holistic, objective process to evaluate the environmental burdens associated with a product or process" [12]. The Life Cycle Assessment methodology was applied to estimate following environment impacts: global warming potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical ozone formation potential, non-hazardous waste disposal.

The product existence is understood as the life cycle process of a building product (Fig. 2) which is connected with energy flow, resource consumption and pollutant emissions that can vary depending on boundary conditions. All stages of building material life cycle that create supply chain process include raw material extraction, manufacturing of these raw materials, material transport, construction process, use and maintenance phase and finally end of the product that can be demolished, disposed, reused, recycled and recovered.

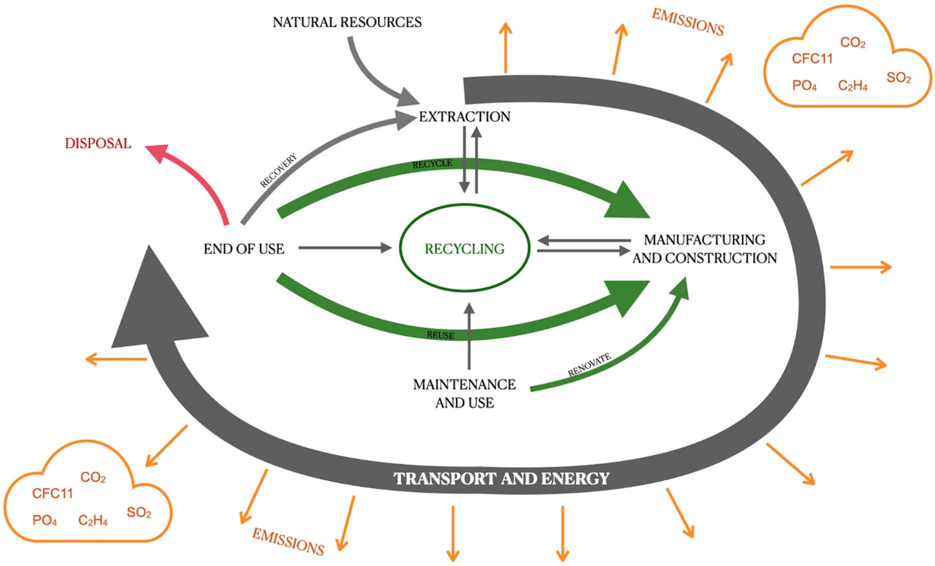

Fig. 2. Life cycle of a product (own study based on [13–15])

Collecting the information of the product over its life span is quite challenging because it would require continuous data collection from several independent stakeholders over a certain period of time. Moreover, it complicates when manufacturing process is integrated with the matter recovered at the end of life stage.

Taking into account, inter alia, the mentioned challenge, it is perfectly understandable that more and more scientists with the development of research are trying to expand LCA analysis to a holistic view called Life Cycle Thinking (LCT). Life cycle thinking distinguish how individual products affect what happens in these processes, so that the effects of certain choices can be adjusted to achieve positive economic, environmental and social impacts.

It can be summarized that LCA serves as the foundation enabling LCT by quantitatively evaluating the environmental impacts of one product or service through its entire life cycle [13].

2.3. LCA stages

The environmental results of LCA analysis covers all life cycle stages from cradle to grave and considers the most important environmental impacts. Modules A1–A3 describe the supply of raw materials, transport and manufacturing of the products while modules A4-A5 take into account transport of the products and construction process. Modules B1-B7 describe the effects generated by use, maintenance and renovation. End of life effect include modules C1–C4 that are associated with disposal, demolition, waste transport and processing. Besides modules A1–C4 that provide information on building life cycle, there is also a separate module – D, that presents the environmental benefits or loads resulting from reuse, recycling and recovery.

Exact stages that are subject to analysis are presented on Fig. 3. The numbers of modules omit A5 – construction-installation process, B1–B3 – use, maintenance and repair of the product, B6–B7 – operational stage and C2–C3 end of life stage – transport and waste processing. The analysis concentrate on preliminary behaviour of the environment impacts described later in the article for the selected stages in both case studies.

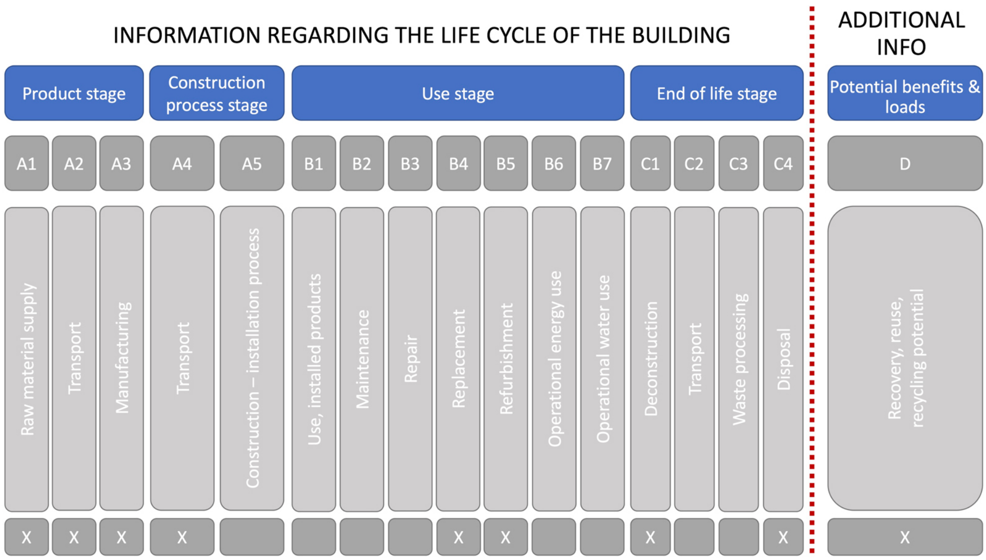

Fig. 3. Life cycle stages included in ecological analysis (based on EN 15978 and EN 15804)

This study is focused on assessing environmental impacts related to the use of building materials, therefore, excluded are the construction - installation process (A5), use (B1), maintenance (B2), repair (B3) and transport of the end of life stage (C2). The operational energy use (B6) and operational water use (B7) stages are also excluded. Despite such limitations imposed in the study, it is possible to assess the actual situation quite accurately. As can be seen in Fig. 4, embodied carbon represents 5 times higher value of annual emissions than the first annual value of operational carbon. Assuming a downward trend of operational carbon, it can be roughly estimated from the graph that embodied carbon accounts for about 41% of emissions over a 31-year horizon also it can be said that it is possible to draw fairly good conclusions based only on calculations of embodied carbon alone.

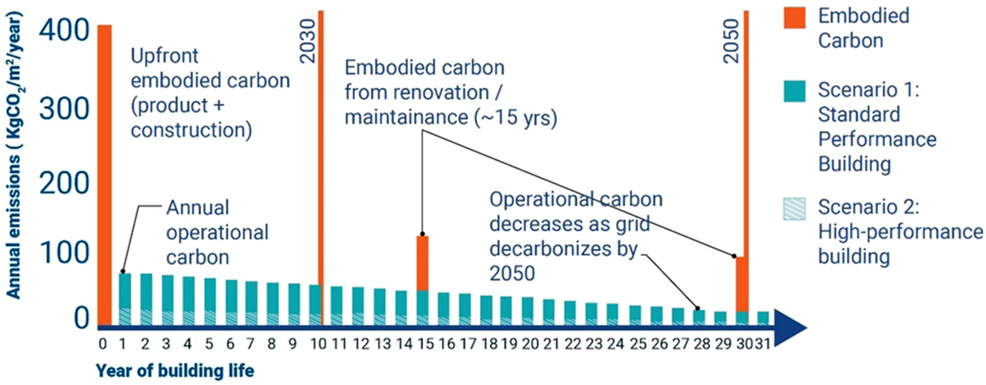

Fig. 4. Materials selection and implementation affects the carbon footprint of a building over its life cycle (Adapted by authors from 2022 Global Status Report for Buildings and Construction)

3. Environment Impact – Methodology

3.1. Analysed environment impacts

Global Warming Potential (GWP)

The atmospheric absorption of radiation that leads to an increase in global temperature is called the greenhouse effect. The gases that contribute most to increasing the greenhouse effect are CO_2, CH_4, CFCs and N_2O. To calculate the global warming potential, it is necessary to take into account the time frame of the gas in the atmosphere in order to determine the gas exposure time horizon. Typically, the overall effect is observed over 100 years in order to account for variations over the entire lifetime. The global warming potential of all GHG emissions is measured in kilograms of carbon dioxide equivalent (kg CO_2 eq). This means that all GHGs are compared with the global warming potential of 1 kg of CO_2.

$$\mathrm{GWP}_j = \frac{\int_0^{\tau} a_i c_i(\tau)\mathrm{d}\tau}{\int_0^{\tau} a_{\mathrm{CO_2}} c_{\mathrm{CO_2}}(\tau)\mathrm{d}\tau} \tag{3.1}$$

where: a_i – efficiency due to a unit increase in atmospheric abundance of the substance, $\mathrm{W(m^2{\cdot}kg)^{-1}}$, c_i – time-dependent decay in abundance of the i-th, $\mathrm{kg{\cdot}m^{-3}}$, $a_{\mathrm{CO_2}}$ – efficiency due to a unit increase in atmospheric abundance of the CO_2, $\mathrm{W(m^2{\cdot}kg)^{-1}}$, $c_{\mathrm{CO_2}}$– time-dependent decay in abundance of the CO_2, $\mathrm{kg{\cdot}m^{-3}}$, τ – time horizon given in years

Acidification Potential (AP)

The acidification potential determines the effect of various substances on the acidification of the aquatic and terrestrial environment. As a result of the emission of acidifying substances, the value of the pH indicator is lowered in the aquatic systems, which in turn leads to the release of heavy metals. The basic substances that increase the acidity of the environment are, among others SO_2, NO_x, NH_3, HF, HCl. The most significant sources are combustion processes in electricity, heating production, and transport. The contribution to acidification is greatest when the fuels contain a high level of sulphur. The reference substance for the acidification potential is sulphur dioxide SO_2.

$$AP_i = \frac{v_i}{v_{SO_2}} \tag{3.2}$$

where: v_i – the number of potential H^+ per mass unit of the i-th substance, mol·kg^{-1}, v_{SO_2}– the number of potential H^+ per mass unit of the reference substance (SO_2)

Eutrophication Potential (EP)

The eutrophication potential of the terrestrial and aquatic environment is determined in the form of an equivalent amount of PO_4. It is the potential to cause over-fertilization in water and soil and may result in increased growth of biomass. The most significant phosphorus emissions come from municipal and industrial wastewater treatment plants and from agricultural land.

$$EP_i = \frac{\frac{v_i}{M_i}}{\frac{v_{ref}}{M_{ref}}} \tag{3.3}$$

where: v_i – share in the eutrophication potential of one mole of i-th substance, v_{ref} – eutrophication potential of one mole of reference substance (PO_4), m_i – molar mass of the i-th substance, M_{ref} – molar mass of the reference substance

Ozone Depletion Potential (ODP)

The potential of the ozone layer degradation allows for the determination of the amount of the ozone depleting substance in the stratosphere, determined in the form of a load equivalent. The layer of stratospheric ozone protects inhabitants from hazardous ultraviolet radiation. The depletion increases the risk of skin cancer and cause damage to plants. The potential impacts of all relevant substances for ozone depletion are converted to their equivalent of kilograms of trichlorofluoromethane. The unit of measurement is in kilogram of CFC-11 equivalent.

$$ODP_j = \frac{(\Delta O_3)_i}{(\Delta O_3)_{CFC-11}} \tag{3.4}$$

where: $(\Delta O_3)_i$ – decrease in ozone O_3 concentration in the stratosphere in a state of equilibrium as a result of the emission of the i-th substance, kg/year, $(\Delta O_3)_{CFC-11}$ – decrease in ozone O_3 concentration in the stratosphere in a state of equilibrium as a result of the CFC-11 emission, kg CFC-11/year

Photochemical Ozone Formation Potential (POFP)

The photochemical ozone formation potential means formation of ozone of lower atmosphere and expresses the activity of a mass unit of a substance in the formation of ozone in the troposphere which is harmful. It attacks organic compounds in living organisms and increases the frequency of respiratory problems when photochemical smog is present in cities. Ethylene

C_2H_4 was used as reference substance to present results of the *POCP* equivalent.

$$\mathrm{POCP}_i = \frac{\frac{a_i}{b_i}}{\frac{a_{\mathrm{C_2H}}}{b_{\mathrm{C_2H}}}} \tag{3.5}$$

where: a_i – change in ozone O_3 concentration as a result of the i-th substation VOC emission, b_i – cumulative emission of the i-th VOC substance up to that time, $a_{\mathrm{C_2H}}$– change in ozone O_3 concentration as a result of the C_2H_2 emission, $b_{\mathrm{C_2H}}$ – cumulative emission of the C_2H_2 substance up to that time

Non-hazardous waste disposed (NHWD)

Non-hazardous waste is any waste that does not cause harm to people or the environment [16]. Environmental Protection Agency recognized that no single waste management approach is sufficient to manage all materials and waste streams under all circumstances. EPA developed the non-hazardous materials and waste management hierarchy. "An important issue of environmental protection process is the solid waste management (SWM), that includes responsible planning of collecting, transporting, processing and disposing of hazardous and non-hazardous solid waste material" [17]. The EUTOSTAT created Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics called Guidance on EWC-Stat Waste Categories that presents common understanding of waste classification where list of non-hazardous waste can be found.

Table 1 summarizes information on all environmental impacts that were used in the analysis.

Table 1. Environment impacts used in the analysis (own study)

Impact category	**Abbreviation**	**Unit**
Global Warming Potential	GWP	$kgCO_2e$
Acidification Potential	AP	$kgSO_2e$
Eutrophication Potential	EP	$kgPO_4e$
Ozone Depletion Potential	ODP	kgCFC-11e
Photochemical Ozone Formation Potential	POFP	kgC_2H_4e
Non-Hazardous Waste Disposed	NHWD	kg

4. Results of the environmental life cycle assessment of warehouse-type constructions

4.1. Case studies – warehouse buildings

The environmental impact analysis is based on an LCA analysis of two warehouses projects located in Poland. Calculations and related datasets are compliant with ISO 14040/14044, EN15804 and BREEAM International NC 2013 and 2016 requirements.

For the purposes of this article, the descriptions of buildings were adopted as Warehouse 1 (W1) (Fig. 5) and Warehouse 2 (W2) (Fig. 6). The basic building material of both warehouses is reinforced concrete. The envelope consists of insulated sandwich panels. The overall weight of building W2 materials is 22% higher comparing to W1. The amount of the materials used for foundations is almost equal – the difference of 1%. Quite significant contrast can be noticed for interiors. Building W2 standard of interior finishes is remarkably higher – the variety of used materials is more complex than it is in case of W1.

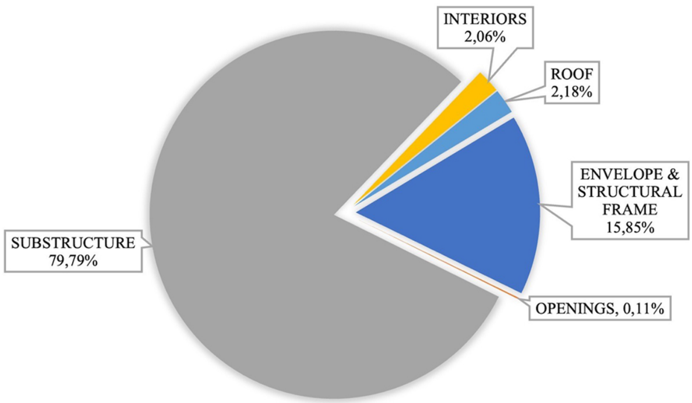

Fig. 5. Share of material groups in the total tonnage of Warehouse 1 (own study)

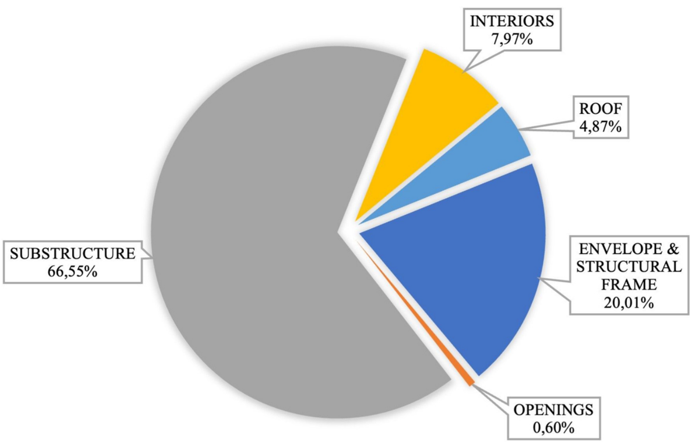

Fig. 6. Share of material groups in the total tonnage of Warehouse 2 (own study)

The conducted analysis do not include landscaping – it covers only the building structure itself. Building W2 is characterized by over 30 different building materials while building W1 by almost 20. Additionally, ready-mix concrete used for structural frame of building W1 contains 10% recycled binders in cement. The amount of each material used in the building was derived from the bill of quantities. In order to present the results in a legible way, two ways of material grouping was adopted. All the materials are segregated and merged into larger sets of structural elements or building materials subcategories. The share of selected material groups in the total tonnage is shown in Fig. 5 for Warehouse 1 and Fig. 6 for Warehouse 2. The following division is made:

- SUBSTRUCTURE – Foundation, sub-surface, basement and retaining walls; Excavation; Ground/lowest floor,
- STRUCTURAL FRAME – Columns and load-bearing vertical structures; Structural vertical elements; Upper floors (including horizontal structure); Floor slabs, ceilings, beams,
- ROOF – Roof structure including coverings,
- ENVELOPE – Structure; External walls and façade,
- INTERIORS – Internal floor finishes; Internal wall finishes; Internal walls and partitions; Internal ceiling finishes,
- OPENINGS – External windows and roof lights.

4.2. Analysis of the environmental life cycle assessment of two chosen warehouse-type constructions

The aim of the first analysis was to determine the extent of total environment impact of designed materials on the discussed life cycle stages of the warehouse type structures. Basic data describing sites 1 and 2 used in the analyses are presented in Table 2 and Table 3, respectively.

Table 2. Materials and indicators used in calculations – Warehouse 1 (own study)

Name of material	**Element weight**	**Quantity**	**Unit**	**Estimated global warming kg/CO_2**
Aluminium fixed and single hung windows	55.18–70.78 kg/m^2*	211	m^2	72,265
Calcium silicate masonry unit	5.8–18 kg/pcs.**	422	m^2	59,078
Ceramic floor and wall tiles, 12.7 mm	avg. weight 27.1 kg/m^2	208	m^2	5,615
Ceramic floor and wall tiles, 8.99 – 10.99 mm	avg. weight 23.48 kg/m^2	208	m^2	5,615
Gypsum board, 12.5 mm	9 kg/m^2, 720 kg/m^3	2,699	m^2	17,862
Hollow core concrete slab, 320 mm	426 kg/m^2	426	t	93,731
Insulating ceiling tiles	151–173 kg/m^3***	8,451	m^2	174,541

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Table 2 – *Continued from previous page*

Name of material	**Element weight**	**Quantity**	**Unit**	**Estimated global warming kg/CO_2**
Ready-mix concrete, normal strength, C20/25	240 kg/m^3	461	m^3	14,692
Ready-mix concrete, normal strength, C25/30	280 kg/m^3	3,375	m^3	927,576
Ready-mix concrete, normal strength, C40/50	400 kg/m^3	1,940	m^3	149,759
Reinforced PVC based, synthetic waterproofing roof sheet, 1.2–1.5 mm	2.1 kg/m^2	8,451	m^2	89,244
Reinforcement steel (rebar)	0.222–6.31 kg/m****	291	ton	570,686
Rock wool insulation	28 kg/m^3	8,451	m^2	546,524
Steel faced sandwich panels with mineral wool core	22 kg/m^2, 150 kg/m^3	4,548	m^2	220,933
Steel tiles, panel roof tiles, trapezoidal sheets and cassettes	4.7 kg/m^2	7,892	m^2	238,330
Water-borne interior wall paints	0.284 kg/m^2	3,435	kg	8,700

* Range is given due to different window sizes.
** Range due to different dimensions of the elements.
*** Range due to different type of ceiling tiles.
**** Range is given due to different rebar diameters.

Table 3. Materials and indicators used in calculations – Warehouse 2 (own study)

Name of material	**Element weight**	**Quantity**	**Unit**	**Estimated global warming kg/CO_2**
Aluminium entrance doors	38.9 kg/m^2	183	m^2	30,197
Aluminium frame window, triple glazed, 1.23 ×1.48 m	62.62 kg/m^2	240	m^2	57,860
Window, skylight, triple glazed, 1.2 ×1.2 m	50.1 kg/m^2	135	m^2	38,365
Skylight, smoke vent, 1.2 ×1.2 m	103.28 kg/m^2	86	m^2	28,047
Autoclaved aerated concrete	550 kg/m^3	7,550	m^2	538,217

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Table 3 – *Continued from previous page*

Name of material	**Element weight**	**Quantity**	**Unit**	**Estimated global warming kg/CO_2**
Ceramic floor and wall tiles, 7.9 mm	avg. weight 17.57 kg/m^2	906	m^2	218,500
Concrete precast elements, paving plates, tiles, window sills	15 kg/m^3	7,561	m^2	515,317
EPS thermal and acoustic insulation	400 kg/m^3	90	m^3	4,822
Hollow core concrete slabs, C40/50	650 kg/m^3	980	m^2	87,383
Lightweight concrete block, with expanded clay aggregate	650 kg/m^3	56	m^2	6,760
Lime cement mortar	1,800 kg/m^3	3,500	kg	530
Mineral wool (flat roof insulation)	145 kg/m^3	31,040	m^2	411,876
Mortars for laying tiles	5.42 kg/m^2	3,450	kg	1,496
Polyester reinforced thermoplastic waterproofing membrane	1,750 g/m^2	15,520	m^2	179,504
Polyethylene vapor barrier membrane, UV resistant, 0.2 mm	0.185 kg/m^2	15,520	m^2	118,650
Portland cement, generic, CEM I	2.80 kg/dm^3	1,035	m^2	127,719
Ready-mix concrete, lightweight, C8/10	230 kg/m^3	67	m^3	19,151
Ready-mix concrete, normal strength, C25/30	280 kg/m^3	385	m^3	112,562
Ready-mix concrete, normal strength, C35/45	340 kg/m^3	538	m^3	190,081
Ready-mix concrete, normal strength, C30/37	300 kg/m^3	143	m^3	52,107
Ready-mix concrete, normal strength, C40/50	400 kg/m^3	425	m^3	204,938
Reinforcement steel (rebar), $d = 8 - 32$ mm,	0.40–6.31 kg/m*	126,353	kg	170,577
Rock wool acoustic ceiling panels and tiles, 15 mm	2.0 kg/m^2	3,584	kg	2,516
Sandwich panel, double steel facing and mineral wool insulation	21.9 kg/m^2	1,318	m^2	47,493

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Table 3 – *Continued from previous page*

Name of material	**Element weight**	**Quantity**	**Unit**	**Estimated global warming kg/CO_2**
PIR insulation	11.0 kg/m^3	5,660	m^2	161,876
Screed mortar, cement mortar	1,500 kg/m^3	2,130	kg	428
Steel fibres for concrete reinforcement, d = 0.55–1.00 mm	230 kg/m^3	4,980	kg	3,840
Steel sheets S235, S275 and S355	19.625 kg/m^2	37,883	kg	1,107,854
Steel tiles, panel roof tiles, trapezoidal sheets and cassettes	4.7 kg/m^2	15,200	kg	39,242
Tufted carpet tiles, pile material, total carpet weight	1.8 kg/m^2	498	m^2	5,777
Wall systems (mineral wool, steel studs, gypsum plasterboards)	19.1 kg/m^2	549	m^3	73,331

* Range is given due to different window sizes.

The carbon footprint value data for each material was adopted from popular databases. Figure 7 describes participation of each environmental impact in particular stage as a percentage. Due to the fact that current research omit facilities operation phase that is recognized as the main agent for the most of impact categories, the influence of second main agent is better emphasized. Undoubtedly, product stage contributes to the largest share of impacts that were analysed – it equals at least 80% for most of the impact categories. In most cases the share of environmental impact determined by transport (A4) do not exceed 2.5% of the whole life cycle impacts. Only transport (A4) of building W1 substructure materials contributes to significant level of ozone depletion potential. A detailed analysis of replacement phase B4–B5 revealed that interiors and roof structure are responsible for the highest environment impact share in most cases. The end of life phase is characterised by the highest level of "non-hazardous waste disposed" indicator. Potential loads and benefits are worth to pay attention – both buildings reveal quite satisfying reuse, recycle, recovery potential. Further analysis proves that steel and concrete used for warehouses significantly contribute to recycling potential increase.

A comparative analysis of all impacts for the product stage A1–A3 for both warehouses pays particular attention to large discrepancies in the group of interiors and the group of openings. Differences appear mainly due to the different standards of interior finishing and in the case of openings due to their number. The W2 building has 5 times more window openings, which contribute to rather high emissions when comparing this group of materials for building W1. The discrepancy between substructure is revealed only in case of ozone depletion potential. ODP potential of substructure W2 is 18 times higher than value received for W1 substructure. The other environment impacts do not indicate substructure exceptional discrepancies. The heaviest structural part of both buildings – foundations is also responsible for the highest tonnage of non-hazardous waste. Among all of the structural elements, the

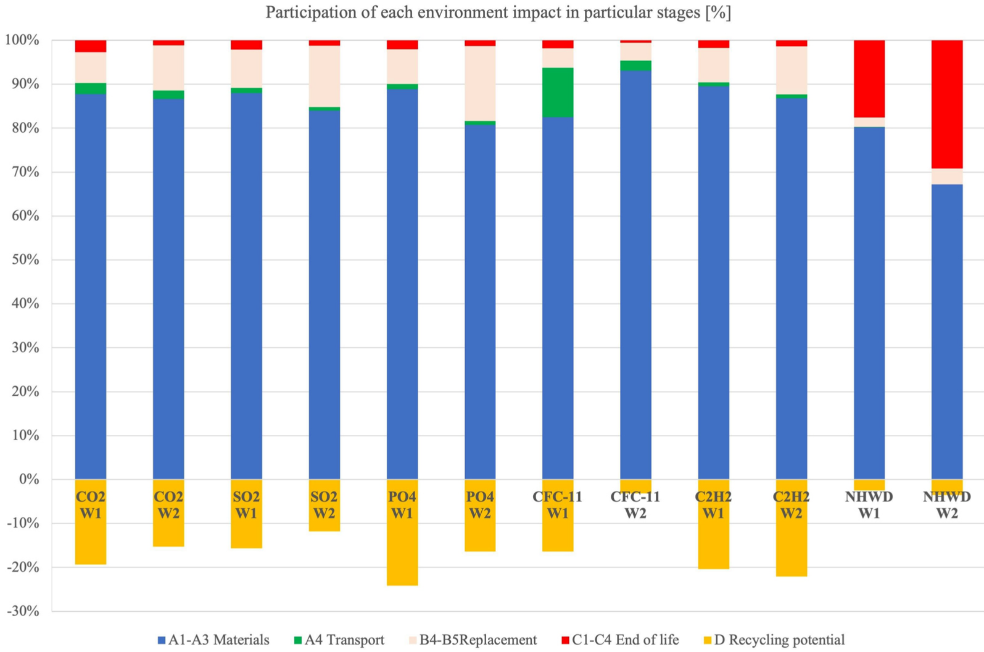

Fig. 7. Environment impacts in particular stages – warehouses comparison (own study)

greatest discrepancies between analysed environment impacts are visible in the roof structure. W2 roof is characterized by greater values of impact factors. A brief summary of the roof results is following:

- global warming potential: W2 = 3.23 ×W1,
- acidification potential: W2 = 3.71 ×W1,
- eutrophication potential: W2 = 5.17 ×W1,
- ozone depletion potential: W2 = 4.55 ×W1,
- photochemical ozone formation potential: W2 = 2.08 ×W1,
- non-hazardous waste disposed: W2 = 1.34 ×W1.

Eutrophication potential is strongly influenced by steel sheets and polyester membranes used in the roof construction of building W2. The same materials are responsible for increased ODP of the W2 roof. In case of acidification potential, beside steel sheets, the mineral wool shows disadvantageous behaviour. The exemplary graph – Fig. 8 depicts summary of the results received for eutrophication potential.

When analysing the specified materials for the A1–A3 stage, attention should be paid to mentioned above steel sheet (warehouse W2), which is characterized by the highest result for all six actions – the selected ones are shown in Fig. 9 and at the same time reveals the highest reuse potential. The difference in the results appearing in the tiles is caused not only by the choice of material but also by the quantity, because the W1 building is covered with five times the amount of tiles used in the W2 building. Additionally, in the W2 warehouse, wool was used

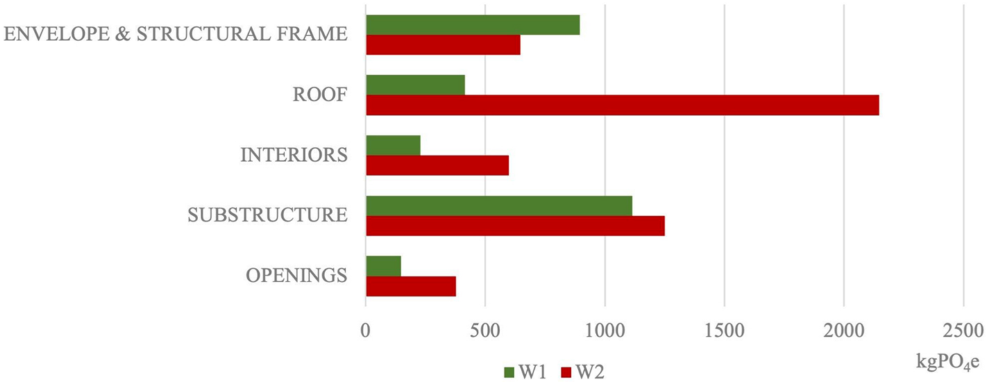

Fig. 8. Phase A1–A3 Eutrophication Potential – comparison of building W1 and W2 (own study)

to insulate the roof, the surface ratio of which to the insulation panels of the W1 warehouse was over 3.5 times more. When monitoring the results of roofing membranes, it should also be noted that, depending on the parameters of the materials, they may significantly contribute to negative environmental impacts and are often not a subject to such a detailed analysis of environmental parameters as e.g. insulation wool.

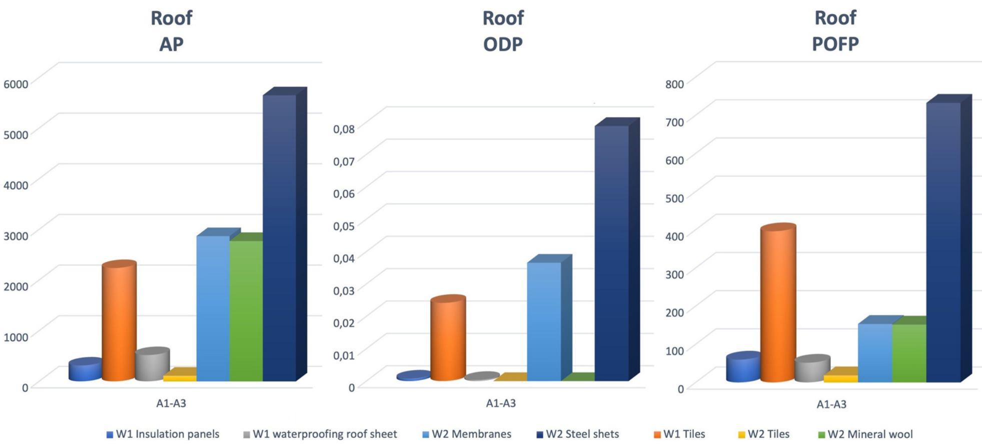

Fig. 9. Phase A1–A3 – impacts of roof materials for W1 and W2: Acidification Potential (left), Ozone Depletion Potential (middle), Photochemical Ozone Formation Potential (right) (own study)

In order to sum up above described results a juxtaposition of global warming potential for materials was conducted. Figure 10 presents participation of materials groups on GWP in both buildings. Obviously slighter different structure and larger cubic capacity of warehouse W2 contributes to higher total tonnage of CO_2e emission. However, the aim of the Fig. 10 is not to compare exact amount of emissions but to indicate the share of certain materials in the total value of GWP for each building. The graph confirm that main structural elements i.e. steel, concrete and precast elements are characterized by most significant impact. Only steel and concrete are responsible for around 50% of total value of GWP. The third material that has a significant impact on environmental damage is insulation. In the total GWP statement the share of membranes emissions is not strongly emphasized, however previous analyses indicated their disadvantageous impact.

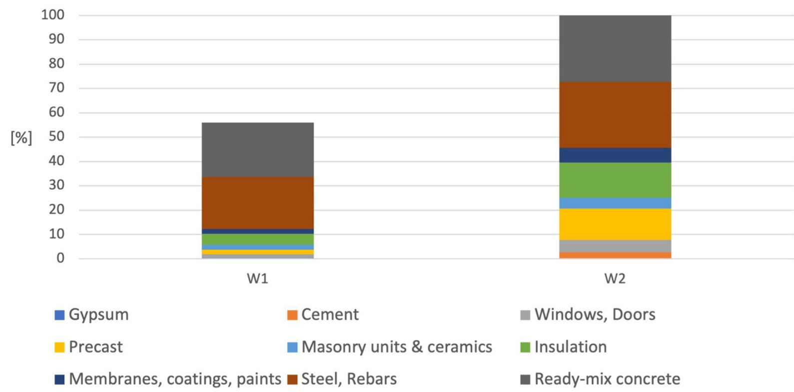

Fig. 10. Phase A1–A3 Global Warming Potential – materials share in W1 and W2 (own study)

5. Discussion

The results show the importance of the selection of appropriate materials and confirm the test results presented in the literature, which emphasize the essence of the emission at the stage of production [10] of the materials and prove the high level of concrete and steel emissivity [18]. Analyses revealed differences in impacts depending on different warehouse type designs. Results pay attention to membranes which, despite their small amount compared to concrete, can also have a large impact on the environment. The conducted considerations present the differences between all six environmental impacts and indicate the value emissions for the product phase of the discussed materials for specific cases, showing the differences between them.

In terms of individual building materials of warehouse W1, ready-mix concrete elements has the greatest impact for the indicator "global warming potential" containing 38% of the development's embodied carbon. Subsequently it is followed by metal elements (33%), plastic, membrane and roofing elements (8%) and insulation (7%). In terms of individual building materials of Warehouse W2, metal elements have the greatest impact for the indicator "global warming potential" – almost 25% of the development's embodied carbon. This is followed by ready-mix elements (24%) and then precast elements (19%).

Referring to similar studies, the authors would like to draw attention to the fact that research to date on the carbon footprint and environmental impacts in general has focused primarily on the global impact of the carbon footprint on the environment. Examples include in article [19] describing a comparison of scenarios of limited emission reductions with the resulting potential reductions in greenhouse gas emissions today and over time to 2045. The authors in [20] based their analysis on a building in Westerlo, Belgium. They performed a parametric structural-typological analysis, automated using One Click LCA (Life Cycle Assessment) software and Microsoft Excel with 21 design alternatives and 630 iterations. Three key performance indicators were examined: structural system, environmental impact of materials and materials. The environmental impact of both structural systems and reused building materials was assessed for four structural system scenarios. However, the full life cycle assessment focused mainly on carbon neutrality. The results say that the weight of the building material, the potential for reuse of materials and the ability to dismantle the structure are the most influential factors in carbon-neutral buildings.

Authors often focus on a single material, very often the concrete mix or reinforcement. For example, the paper [21] presents the results of a preliminary study of carbon contained in reinforced concrete as a function of: concrete strength class, steel strength, mix design, etc. The results showed that there is a wide range of ECraw expressed in $kgCO_2/kg$ of reinforced concrete (0.06–0.47). The general observations made in the research on concrete and steel are generally consistent with those shown in this article. Research on the design of concrete mixtures their classes and the ingredients and admixtures used to reduce the CO_2 equivalent is needed. However, our article analyses all the main materials used in warehouses and other environmental aspects.

6. Conclusions

Analysing the presented results of the case studies of warehouse buildings, it should be stated that the product stage is a particularly important phase of the life cycle, as it shows the highest levels of environmental indicators. Paper indicates the necessity of reasonable material choices due preponderant influence of stages A1–A3 in the whole life cycle. It is particularly important on account of the fact that the supply of raw materials, transport and manufacturing of the products connects with the design stage, the time to make decisions consciously without unnecessarily harming the environment.

Further research will be conducted in order to enrich analysis with more detailed results. In the next steps choice of the specific materials and their influence on results in each phase will be determined. Greater attention will be paid to new innovative and recovered materials. Recently introduced low carbon materials should provide new point of view in terms of ecological life cycle analysis. Considerations may be expanded by operational energy influence on LCA study.

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Ekologiczna analiza cyklu życia (LCA) na przykładzie budynków magazynowych

Słowa kluczowe: środowiskowa ocena cyklu życia LCA, etapy LCA, wpływ obciążeń środowiska, GWP, materiały budowlane, magazyn

Streszczenie:

Współczesne społeczeństwo intensywnie podąża za ideą zrównoważonego rozwoju, aby przeciwdziałać skutkom globalnych decyzji, które doprowadziły do pogorszenia stanu środowiska. Idea ta opiera się na trzech głównych filarach: ochronie środowiska, efektywności ekonomicznej i równowadze społecznej. Kwestie ochrony środowiska są nieodłącznym elementem debaty publicznej od czasów rewolucji przemysłowej. Nieustannie, na całym świecie podejmowane są nowe kroki i strategie, ukierunkowane na wprowadzanie i promowanie zrównoważonego rozwoju. Niewątpliwie budowy nie można nazwać procesem przyjaznym dla środowiska, dlatego opracowuje się rozwiązania mające na celu zdefiniowanie negatywnych interakcji budynków, określenie zakresu oddziaływania na środowisko i znalezienie alternatyw w celu poprawy jakości projektu. Budynki oddziałują na środowisko przez całe życie począwszy od wydobycia materiału, budowy, utrzymania aż do zakończenia – m.in. wycofania lub wymiany. Metodologia oceny cyklu życia została wykorzystana do oszacowania kilku oddziaływań na środowisko oraz określenia etapów i materiałów, które wykazują największy wpływ na środowisko. W niniejszym artykule zbadano wpływ obciążeń środowiska dwóch magazynów przy użyciu metodologii LCA, która jest szeroko stosowana w sektorze budowlanym od 1990 r., biorąc pod uwagę etapy cyklu życia od kołyski do grobu z oddzielnym podsumowaniem dla etapu produktu, procesu budowy, etapu użytkowania i końca życia. W artykule nie omówiono fazy eksploatacyjnego zużycia energii budynku. Artykuł koncentruje się na ocenie materiałów budowlanych, a nie eksploatacji obiektów. Przeprowadzona analiza nie obejmuje zagospodarowania terenu – obejmuje jedynie samą konstrukcję budynku. W celu czytelnego przedstawienia wyników materiały zostały pogrupowane.

Analiza uwzględnia następujące wpływy na środowisko:

- Potencjałglobalnego ocieplenia (GWP) – atmosferyczna absorbcja promieniowania, która prowadzi do wzrostu globalnej temperatury nazywana jest efektem cieplarnianym; gazy, które mają największy wkład w powiększenie efektu cieplarnianego to CO_2, CH_4, CFCs oraz N_2O,
- Zakwaszenie środowiska (AP) – potencjał zakwaszenia określa wpływ różnych substancji na zakwaszenie środowiska wodnego i lądowego; w wyniku emisji substancji zakwaszających obniża się wartość wskaźnika pH w systemach wodno-lądowych co w następstwie prowadzi do uwolnienia metali ciężkich,
- Eutrofizacja środowiska (EP) – potencjał eutrofizacji może powodować nadmierne nawożenie wody i gleby i może skutkować zwiększonym wzrostem biomasy,
- Degradacja stratosferycznej warstwy ozonowej (ODP) – potencjał degradacji warstwy ozonowej pozwala na określenie ilości substancji wykazującej niszczące działanie na ozon w stratosferze wyznaczanej w formie równoważnika obciążeń,
- Powstawanie ozonu troposferycznego (POFP) – potencjał fotochemicznego tworzenia ozonu wyraża aktywność jednostki masy danej substancji w tworzeniu ozonu w troposferze,
- Odpady nie stwarzające zagrożenia (NHWD) – odpady inne niż niebezpieczne to wszelkie odpady, które nie powodują długoterminowych szkód dla ludzi lub środowiska.

Analizę przeprowadzono w celu określenia stopnia oddziaływania projektowanych materiałów na poszczególne etapy cyklu życia konstrukcji typu magazynowego. Niewątpliwie w przypadku obu magazynów największy udziałanalizowanych wpływów na środowisko widoczny jest na etapie produktu. Dla

większości analizowanych oddziaływań wynosi on co najmniej 80%. W celu zidentyfikowania różnic występujących w stworzonych grupach elementów dokonano szczegółowego porównania materiałów użytych do budowy obu dachów ze względu na rozbieżności w omawianej grupie. Największe efekty ekologiczne osiągane są na etapie produktu (A1–A3). Etap transportu (A4) i etap wycofania z eksploatacji (C1, C4) w konstrukcji dachu w niewielkim stopniu przyczyniają się np. do wzrostu emisji ekwiwalentu dwutlenku węgla. Analizując poszczególne materiały dla etapu A1–A3 należy zwrócić uwagę na blachę stalową, która generuje najwyższe emisje i jednocześnie wykazuje największy potencjał ponownego wykorzystania. Podsumowując otrzymane wyniki studiów przypadku budynków magazynowych, stwierdzić należy, że etap produktu jest szczególnie ważnym etapem cyklu życia, gdyż wykazuje najwyższe poziomy wpływów emisyjnych spośród analizowanych etapów. W artykule wskazano materiały dla obu budynków, które odpowiadają za największe oddziaływania. Wyniki uwydatniają wagę rozważnego doboru materiałów i wskazują kierunek dla dalszej analizy.

Received: 2023-02-18, Revised: 2023-06-19