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Research paper

Integrated analysis of costs and amount of greenhouse gases emissions during the building lifecycle

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Abstract: More than 6 billion square metres of new buildings are built each year. This is about 1.2 million buildings. If we translate these figures into carbon footprint (CF) generated during the construction, it will be approximately 3.7 billion tons of carbon dioxide. The contractors all over the world – also in Poland – decide to calculate the carbon footprint for various reasons, but mostly they are compelled to do so by the market. The analysis of costs and emissions of greenhouse gases for individual phases of the construction system allows implementing solutions and preventing a negative impact on the environment without increasing the construction costs. The share of each phase in the amount of produced carbon for construction and use of the building depends mainly on the used materials and applied design solutions. Hence, the materials and solutions with lesser carbon footprint should be used. It can be achieved by using natural materials or materials which do not need much energy to be produced. The author will attempt to outline this idea and present examples of integrated analysis of costs and amount of carbon footprint during the building lifecycle.

Keywords: cost estimation, carbon footprint, construction

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1. Introduction

The measure of greenhouse gases (GHG) is the carbon footprint defined by the standard ISO 14067 [6]. According ISO standard carbon footprint of a product (CFP) is a sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change. The carbon footprint is a sort of ecological footprint which includes emissions of carbon dioxide (CO_2), methane (CH_4), dinitrogen monoxide (N_2O) and other greenhouse gases, inter alia industrial gases such as sulphur hexafluoride (SF_6), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) expressed in CO_2 equivalent.

The building sector is responsible for consuming about 40% of global energy and global CO_2 emissions. More than 66% of the carbon emissions from a building occur during the operation stage of the life cycle of a building [8]. The most effective changes to reduce a building's carbon output are: increasing the service life span and reducing the energy consumption per building area [8].

Taking into account the Industrial Ecology theory, Circular Economy (CE) is an industrial economic model that is restorative and regenerative by intention and design [9]. In the case of construction, its purpose is effective resource management, minimizing construction waste and reducing the amount of pollution and toxic waste through careful design. Besides, waste management continues to be a challenge for developing countries [5]. Górecki in his paper showed a scale that will provide information to the company itself and its stakeholders, on the degree of long-term sustainability of the construction company, and the degree of implementation of CE [11].

Due to the costs of construction and use, the calculations of carbon footprint in the building lifecycle must be closely related to the analysis of works and construction elements. The analysis of costs and emissions of greenhouse gases for individual phases of the construction system allows implementing solutions and preventing a negative impact on the environment without increasing the construction costs. The share of each phase in the amount of produced carbon for construction and use of the building depends mainly on the used materials and applied design solutions. Hence, the materials and solutions with lesser carbon footprint should be used. It can be achieved by using natural materials or materials which do not need much energy to be produced. The author will attempt to outline this idea and present examples of integrated analysis of costs and amount of carbon footprint during the building lifecycle. Sustainability should start with the very design of buildings and construction projects. In this area, there is room for selecting materials, parameters of importance, and objectives for successive output with a view to sustainability [10].

2. Greenhouse gases emissions in Poland and the world

Among all greenhouse gases, the carbon dioxide emissions are the largest and constitute over 80% of the total emissions of greenhouse gases. However, the remaining gases absorb heat much more effectively that carbon dioxide. The European Union is the third emitter of greenhouse gases in the world, just behind China and the United States. In terms of emitter type, in 2017 the energy was responsible for 80.7% of greenhouses gases emissions (in which about 1/3 is transport), agriculture for 8.72%, industrial processes and use of products for 7.82%, and waste management for 2.75%. Figure 1 presents the total greenhouse gases emissions, excluding the land use and forestry, expressed in CO_2 equivalent in selected EU countries. As seen in Fig. 1, Poland is among the EU leaders in greenhouse gases emissions. The largest emitter is Germany, and Poland belongs to group two along with the UK, France, Italy and Spain.

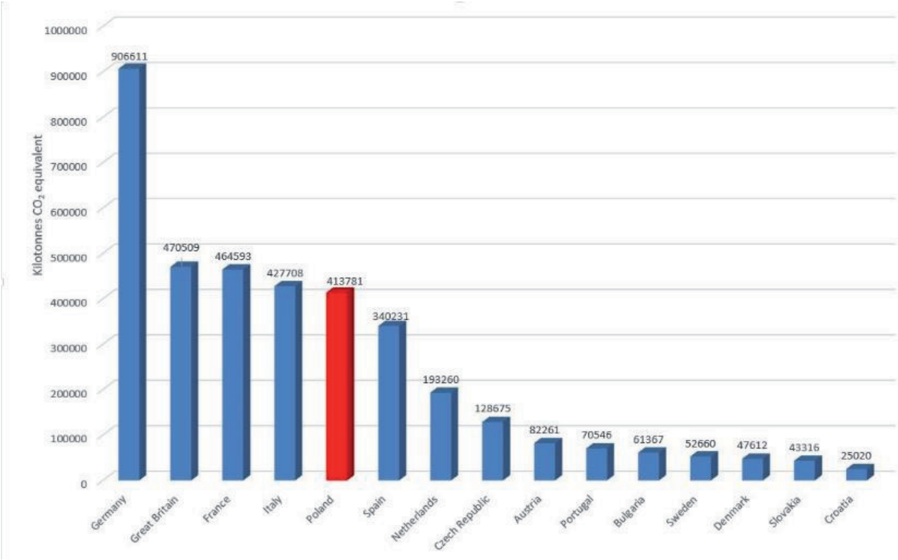

Fig. 1. Total greenhouse gas emissions in selected EU countries (source: Eurostat).

The construction sector is responsible for 28% of global CO_2 emissions annually (residential and non-residential construction), and in addition the so-called embodied carbon constitutes 11% of the global emissions (Fig. 2). The embodied carbon is problematic because it is so to speak “blocked” after the construction of a building and nothing can be done about it, contrary to the emissions caused by the building use which can be reduced by e.g. using environmentally-friendly energy sources.

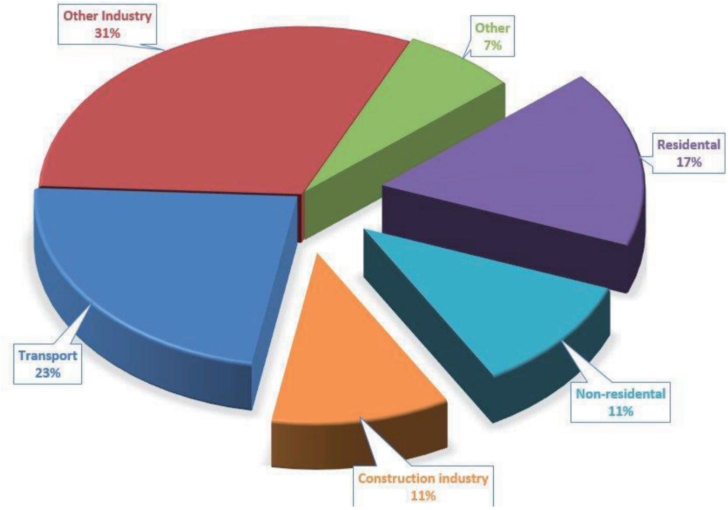

Fig. 2. Global CO_2 emissions by sector (source: Adapted from IEA, Energy Technology Perspectives, buildings model, www.iea.org/buildings)

3. Carbon footprint in the building lifecycle

The construction contractors must themselves determine the limits and scope for which they calculate the carbon footprint. Similarly to the costs calculations, the carbon footprint should be calculated for the entire building lifecycle. In case of costs LCC is a key element in the assessment of environmental sustainability in construction. It provides a tool for the economic evaluation of alternative sustainability options exhibiting different capital, operating costs or resource usage the life cycle of the building would end with its demolition and the resale of the building plot on which it was built (building life cycle termination of the “from cradle to grave” type) [12]. The LCC analysis is to show that all savings in the building use phase justify the choice of accepted and sometimes more expensive solutions. So, it is worthwhile achieving the lowest long-term cost of project implementation and use. Usually, the costs of use, maintenance and disposal are a few times higher than all other initial costs. Hence, including them in the analysis gives a fuller picture of the project cost-effectiveness [1]. The life-cycle cost of a building is the basis for making long-term investment decisions, but also has a significant impact to increase their environmental performance (lower energy consumption, lower CO_2 emission). Increasing the initial capital costs typically results in lower running costs in the life cycle and an increase in the final value of the property [4]. The authors of the article [7] propose introducing flexibility i.e. the consideration of different scenarios which anticipate changes in the configuration of parameters of the object in the cycle of its life. The examinations of the authors of the article are based on the scenario analysis expanded on simulation method.

There are then basically three possibilities which depend on the adopted building lifecycle scenario:

- cradle to gate,
- cradle to grave,
- cradle to cradle.

The first possible solution to end the life cycle is the “from-cradle-to-gate” approach. Analyses with this type of approach may end, for example, after processing raw materials making up the finished element or at the stage of its production. The analysis would cover only the two initial phases of the life cycle of the building component, that is, the programming (cradle) and implementation (gate) phases [13].

The second approach, called “Cradle to Grave”, is firmly established in Polish conditions and finishes with the demolition of the analysed building component or the whole building. Finally, the “Cradle to Cradle” mode is a specific type of the “Cradle to Grave” assessment, where the end-of-life disposal step for a product is a recycling process [16].

Consequently, the emission of ecological footprint expressed as CO_2 equivalent should be considered in a few successive phases (Fig. 3):

- Production phase – includes carbon dioxide emissions related to the extraction of raw materials, their transport to the production site and transformation to construction products,
- Construction phase – includes the transport of construction products and processes related to the building construction,
- Use phase – covers the period from the completion of construction works to the demolition of the building, generating a wide range of emission sources related to the use of the building (e.g. heating, cooling, power consumption, water supply or building repairs and maintenance),
- End-of-life phase – includes the demolition and transport processes during the demolition.

The “cradle to cradle” scenario should also account for additional external impacts related to the post-demolition process connected with the reuse of recycled or recovered materials.

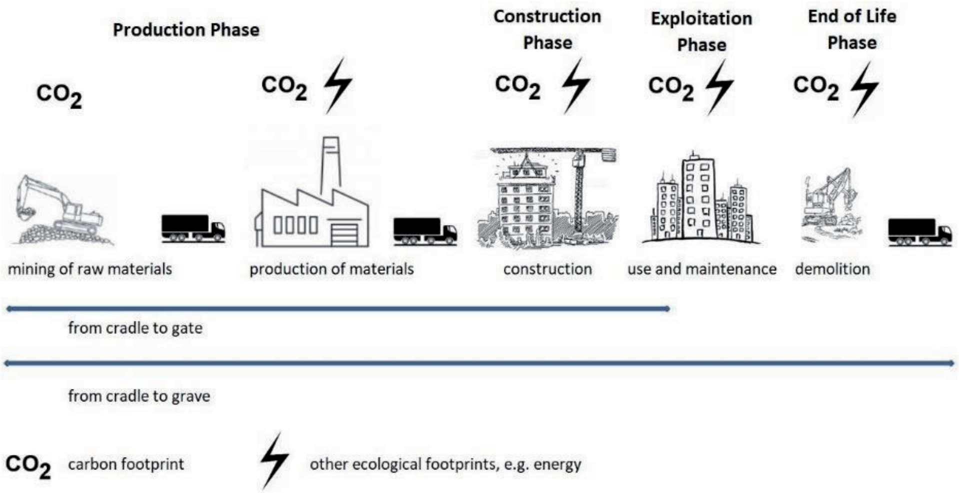

Fig. 3. Generating an ecological footprint over the building's life cycle (own study).

4. Examples of integrated cost and carbon footprint calculations

The carbon footprint calculation and also the costs calculation can be made at any level of detail. In the paper, the author has presented calculations for the selected material and for typical buildings, analysing the carbon footprint at the production phase and at the construction phase, as well as the material purchase costs and the building construction costs. The comparative approach based on integrated calculations of the CO_2 emissions and of the costs can be used by decision makers to make initial design decisions. The main goal of such analysis is to start a discussion about the costs and carbon effectiveness and to perform a feasibility assessment of design alternatives. Results obtained by the authors in [2] demonstrated than the optimisation methodology can effectively compute solutions that improve the cost and carbon performance of the conventional designs without compromising their constructability.

4.1. The construction materials – concrete mixture

Table 1 presents the CO_2 emissions during the production of typical construction materials.

Table 1. Fossil carbon emitted in production (source: own based on [14]).

Type of material	CO_2e [g/kg]	CO_2 fossil [g/kg]	CH_4 [g/kg]	N_2O [g/kg]	CO_2 uptake [g/kg]	Cost [€/ kg]
Chipboard (Raw)	409	409	0	0	1564,2	0,28
Gypsum Plasterboard	1967	1846	4,03	$6,8 \times 10^{-2}$	0	0,47
Plywood (Standard Birch)	718	650	2,7	$3,3 \times 10^{-3}$	1188	1,27
Massive Parquet	2942	2942	0	0	1696	1,38
Dry wood	108	101	0,25	0,00012	1835	0,12
Glass Wool	3148	2909	7,7	0,16	0	3,63
Polystyrene (EPS)	3300	2500	31	0	0	1,86
Wood fibre insulation	243	0	0	0	1240	1,02
Aerated Concrete Block	442,3	429,2	0,49	$3,5 \times 10^{-6}$	0	0,15
Aluminium (Extrusion profile)	2264	2147	4,2	$4,2 \times 10^{-2}$	0	0,37
Ceramic tiles	612,5	600	0,5	0	0	0,93
Lightweight Concrete Block	239,7	231,7	0,29	$3,1 \times 10^{-6}$	0	2,36
Gypsum Stone ($CaSO_4$)	2,7	2,4	$3,6 \times 10^{-3}$	$6,2 \times 10^{-4}$	0	0,45

As we can see in Table 1, the largest carbon dioxide emissions are caused by such materials as steel or aluminium; glass, cement, or steel recycling have significantly lesser emissions; and the production of concrete, bricks and of course wooden components has relatively low emissions.

Table 2 shows typical composition of concrete mixtures used in construction, and Table 3 includes the carbon footprint calculations for their production and transport and their purchase costs.

Tab. 2. Selected concrete mixes and their composition (own study).

Concrete	Cement	Fly ash	Sand	Gravel	Water	Plasticizer	Stabilizer
	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
C20/25	240	100	711	1075	170	1,95	0,67
C12/15	265	0	580	1355	185	0	0
C20/25	315	0	530	1395	175	0	0
C25/30	335	0	520	1410	160	0	0
C30/37	340	190	652	985	160	0	0
C30/37	340	190	700	1060	160	2,38	0,92

Tab. 3. Carbon footprint and costs of selected concrete mixes (own study).

Concrete	Fine Aggregates [CO_2 eq.]	Coarse Aggregates [CO_2 eq.]	Fly ash [CO_2 eq.]	Mixing and Batching [CO_2 eq.]	Transport to concrete Plant [CO_2 eq.]	Concrete Production [CO_2 eq.] (Sum 1-6)	Cement Production [CO_2 eq.]	Sum (7+8) [CO_2 eq.]	Cost [Euro]
1	2	3	4	5	6	7	8	9	10
C20/25	2,024	4,241	2,613	2,877	81,818	93,573	253,26	346,833	65,66
C12/15	1,651	5,346	0	2,877	83,84	93,714	269,53	363,244	56,92
C20/25	1,508	5,504	0	2,877	87,296	97,185	320,389	417,574	63,93
C25/30	1,48	5,563	0	2,877	88,896	98,816	340,732	439,548	67,52
C30/37	0,541	2,572	4,965	2,877	88,435	99,39	345,817	445,207	74,45
C30/37	1,992	4,182	4,965	2,877	92,544	106,56	345,817	452,377	76,68

Table 3 presents the carbon footprint of the concrete mixture production as the CO_2 equivalent. The total CO_2 value for the concrete mixture production is a sum of greenhouse gases emissions during the extraction of sand, gravel, fly ashes and their transport to the concrete batching plant, and during the processes of mixing and batching of the concrete mixture ingredients. The cement production process is considered separately as a sum of the following processes: quarrying, raw materials grinding, cement pyroprocessing, clinker cooling, finish milling, grinding and blending.

The analysis of data included in Table 3 indicates that that the cement production has the greatest carbon footprint which results in large differences depending on the concrete mixture class and ingredients. The remaining ingredients, such as fly ashes and concrete admixtures, do not have a significant impact on the greenhouse gases emissions. The concrete mixture cost is basically proportional to the amount of cement in the mixture.

4.2. Residential buildings

The paper includes also an analysis of costs and carbon footprint for selected residential buildings, again by analysing the production and construction processes of residential buildings. The ORECO2 application was used in the analysis. The OERCO2 tool is an online application that enables the carbon footprint produced in the construction of residential buildings to be estimated [15].

The analysis covered the buildings with the same equipment, finishing and types of systems, except for Building 5 in which ecological solutions were used. The differences in the analysed buildings related mainly to their size, basement, types of foundations, used construction materials, etc. The most important differences are shown in Table 4.

Tab. 4. Carbon footprint and costs of selected residential buildings.

Elements	Building 1	Building 2	Building 3	Building 4	Building 5
Number of floors	1	3	4	5	4
Underground levels	no basement	no basement	no basement	1 basement floor	2 basement floor
Foundation type	strip footings	strip footings	separate footings	foundation slab	foundation slab
Structure type	brick walls	brick walls	reinforced concrete	reinforced concrete	reinforced concrete
Roof	flat	flat	flat	flat	flat
Builded surface	200	800	2000	3500	2000
Cost [€/m^2]	728,83	749,27	664,01	648,29	546,31
Environmental budget (t CO_2eq)	120,31	528,31	1011,50	1724,15	697,54
Environmental budget (t CO_2eq/m^2)	0,6016	0,6604	0,5057	0,4926	0,3488

The analysis covered the buildings with the same equipment, finishing and types of systems, except for Building 5 in which ecological solutions were used. The differences in the analysed buildings related mainly to their size, basement, types of foundations, used construction materials, etc. The most important differences are shown in Table 4.

The analysis of Table 4 indicates that the carbon footprint grows of course with the building size, but decreases per square meter of area. Similarly to the cost, which also decreases with the building size. Thus, it is advantageous both financially and environmentally to erect multi-storey buildings instead of a few smaller ones that would house the same number of people. The Building 5 did not have many amenities which were present in buildings 1-4 such as air-conditioning, solar panels were used to generate energy, ecological materials were used, e.g. wooden blinds and banisters, slate tiles, lightweight concrete blocks and wood finishing on façade. These modifications significantly reduced the greenhouse gases emissions from 0.5-0.6 ton of CO_2eq/m^2 to 0.3488 ton CO_2eq/m^2 at generally lower construction cost reaching even Euro 100 per m^2 for buildings comparable in size. The biggest benefits in terms of greenhouse gases emissions were achieved by reducing the amount of construction ceramics (walls and finishing) in favor of the ecological materials, mostly wood. The costs were reduced by using a larger number of concrete components and abandoning some amenities such as air conditioning and using less expensive finishing. The heating was also changed to ecological. The selected materials from waste biomass can be effectively used to produce energy. In perspective, pellets from wood materials mixture can be a good variant of solid fuel [3].

5. Conclusions

The design solutions, manufacturing technology and used materials play an important part in the general cost and the carbon characteristics of a building. The decision affecting the balance between the cost and carbon effectiveness of structural components should be made early. These decisions are significant because the final design solutions must be effectively coordinated with a wider design team. The examples shown in the paper prove that the carbon footprint of construction works can be reduced without increasing their costs. The carbon footprint calculation and also the costs calculation can be made at any level of detail. The result can be a significant reduction of greenhouse gases emissions which is now an important EU goal according to the Paris climate agreement. Integrated calculations of costs and carbon footprint should now be made for all construction projects.

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Zintegrowana analiza kosztów i wielkości emisji gazów cieplarnianych w czasie życia budynku

Słowa kluczowe: kosztorysowanie, ślad węglowy, budownictwo

Streszczenie:

Analiza kosztów i wielkości emisji gazów cieplarnianych dla poszczególnych faz procesu budowlanego pozwala wdrażać rozwiązania i przeciwdziałać negatywnemu wpływowi na środowisko, bez zwiększania kosztów budowy. Udział w każdej z faz ilości wyprodukowanego węgla na potrzeby wybudowania i użytkowania budynku zależy przede wszystkim od wykorzystanych w nim materiałów oraz przyjętych rozwiązań projektowych. Należy więc stosować materiały i rozwiązania o mniejszym śladzie węglowym. Ślad węglowy zdefiniowany przez normę ISO 14067 [6] to suma emisji i pochłaniania gazów cieplarnianych, wyrażona jako ekwiwalent CO_2 i oparta na ocenie cyklu życia z uwzględnieniem ich wpływu zmiany klimatu. Spośród gazów cieplarnianych emisja dwutlenku węgla jest największa i stanowi ponad 80% całkowitej emisji gazów cieplarnianych.

Można to osiągnąć przez wykorzystywanie materiałów pochodzenia naturalnego lub tych, których produkcja nie pochłania dużo energii. W artykule autor chciał przybliżyć ideę oraz pokazać na przykładach zintegrowaną analizę kosztów i wielkości śladu węglowego w cyklu życia budynku.

Kalkulację śladu węglowego, ale i kalkulację kosztów mozna rozpatrywać na dowolnym poziomie szczegółowości. W artykule autor przedstawił kalkulacje na przykładzie wybranego materiału, ale i przykładowych budynów analizując ślad węglowy w fazie produkcji i w fazie budowy oraz koszty zakupu materiałów i koszty budowy obiektu budowlanego. Prezentowane podejście porównawcze polegające na zintegrowanych obliczeniach emisji CO_2 i kosztów przedstawione w artykule może być wykorzystane przez decydentów, do podejmowania wczesnych decyzji projektowych.

Rozwiązania projektowe, technologia wykonania i użyte materiały odgrywają znaczącą rolę w ogólnym koszcie i charakterystyce węglowej konstrukcji Decyzje wpływające na równowagę między kosztem, a wydajnością węglową składowych elementów konstrukcyjnych powinny być podejmowane wcześnie. Ustalenia te są znaczące, ponieważ ostateczne decyzje projektowe muszą być skutecznie koordynowane z szerszym zespołem projektowym. Pokazane w artykule przykłady udowadniają, że można zmniejszyć ślad węglowy realizowanych robót budowlanych, bez konieczności zwiększania kosztów robót budowlanych. Kalkulację śladu węglowego wraz z kalkulacjami kosztów mozna rozpatrywać na dowolnym poziomie szczegółowości. Efektem obliczeń może być znaczne zmniejszenie emisji gazów cieplarnianych, co jest obecnie istotnym celem UE zgodnie z postanowieniami porozumienia klimatycznego z Paryża.

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