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ANALYSIS OF THE ENVIRONMENTAL IMPACT OF CONSTRUCTION BY ASSESSING THE CARBON FOOTPRINT OF BUILDINGS

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Abstract. The paper presents a methodology for carbon footprint assessment of buildings according to the current European standard. The analytical formulas are proposed to assess the carbon footprint through emissions calculation for the building life cycle including extraction, transportation, and processing of raw materials, construction and installation process, operation, maintenance, and repair, as well as liquidation and disposal. Beyond the life cycle boundaries, the possible benefits from recycling and reuse of building components and materials are considered.

Key words: carbon footprint, emissions, life cycle, building.

1. Introduction

Various types of activities are characterized by varying degrees of environmental impact. About half of all non-renewable resources consumed by mankind are used in construction [1]. The construction industry has a significant impact on most environmental pollution factors. Up to 50 % of world total carbon dioxide emissions come from the construction industry. Greenhouse gas emissions are generated at different stages of the life cycle of the building from the extraction, production, operation, and demolition.

In order to reduce energy use and environmental impact in buildings, the Energy Performance of Buildings Directive [2], the Energy Efficiency Directive [3], and the Circular Economy Action Plan [4] have been established by the European Commission. Regulations, guidelines, and recommendations for the design of buildings with high energy efficiency and low emissions are being developed based on these directives.

The latest generation of international green building standards, such as LEED [5], BREEAM [6], DGNB [7], take into account greenhouse gas emissions from the building at the stage of developing the concept of the future project.

The studies of building parameters and assessment of their impact on the environment are conducted by various scientists in order to develop optimal solutions. The authors [8] provide a thorough overview of the existing assessment practices, analyze the capabilities and limitations of software, and systematize the current database on carbon emissions for building materials and products.

The results of the analysis of the ecological impact parameters of 20 individual houses on various criteria were analyzed in the article [9]. According to the obtained data, the authors proposed ways to simplify the evaluation method by optimizing the data collection process, reducing the number of functional units and impact indicators, limiting the details of life cycle stages, the application of CAD systems.

An analytical method of calculating the embodied carbon of a building object is described in [10]. However, the impact of waste generated during disassembly and disposal has not been taken into account. The method of calculating the emissions for individual residential houses was proposed in the article [11]. The calculation takes into account the stages from the extraction of raw materials to the liquidation of the building but does not estimate the emissions during the operation.

The influence of the structural system and the number of floors of the building on the estimated amount of carbon dioxide emissions is investigated in [12]. Calculations were performed for the studied options and took into account the stages of material extraction, transportation, construction, operation and disassembly.

According to the parametric studies of buildings made of prefabricated reinforced concrete and steel structures, the positive effect of reuse of elements after completing the life cycle has been proved [13, 14]. Reducing the carbon impact is possible through the improvements in production technologies, the use of prefabricated constructions, waste processing to obtain new materials and products, as well as energy production.

Despite the global awareness of global environmental problems and the development of measures to overcome them, the domestic construction industry is only at the beginning of this path. Nowadays, there is a lack of specific targeted design recommendations, which connect all existing and new principles and design approaches taking into account the sustainable circular nature of the functionality of the building.

The aim of this study is to develop a general methodology for the carbon footprint assessment of buildings over the life cycle, which includes raw material supply, construction, operation, maintenance, reuse, and recycling of waste from demolishing.

2. Theoretical background

The assessment of the carbon footprint expressed as the carbon dioxide equivalent for a specific construction project must take into account all emissions that occur during the service life. For correct design, it is also necessary to consider any possibility of reuse and recycling of components and materials, and, if possible, include influences outside the system.

The modular system of life cycle stages laid down in EN 15978 [15] takes into account all stages, which are divided into separate information groups, namely, A1-3 Pre-operational, A4-5 Construction process, B1-7 Operational, and C1-4 End-of-life. These groups can be considered both separately and together with each other to assess the environmental impact of a particular building object.

The pre-operational stage operates with the emissions before construction of the object and includes the supply of raw materials (A1), transportation to the manufacturer's plant (A2), and manufacturing of building materials and products (A3). The construction stage includes the transportation of materials and building elements from the manufacturer to the construction site (A4) and the construction process itself (A5) considering any energy consumption and waste generation during construction, its processing and disposal.

The operational stage is the period from the commissioning of the building to the end of its use. Module B1 considers the energy consumption during the estimated life of the building and the associated carbon emissions. In information group B2, the assessment of influences due to processes of maintenance of necessary functional and technical performance of building components is carried out (e.g., painting floors or walls, periodically checking the serviceability of the heating system, maintenance of gas boilers, etc.).

Table 1

Life cycle stages of a building object according to EN 15978

Life cycle stage	Information group (module)	Process
Pre-operational	A1	Raw material
	A2	Transport
	A3	Manufacturing
Construction process	A4	Transport
	A5	Construction and installation
Operational	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Refurbishment
	B6	Operational energy consumption
	B7	Operational water consumption
End-of-life	C1	Disassembling or demolition
	C2	Transport
	C3	Waste processing
	C4	Disposal
Beyond life cycle	D	Potential for reuse, reprocessing or recycling

Besides, an environmental impact assessment is performed due to the implementation of a set of measures: repair (B3) to restore the serviceability of the building or its components; replacement of the elements which cannot be repaired (B4); refurbishment (B5) to change the parameters of the building or its parts (height, number of floors, apartment layout), including the addition of floors, reconstruction, replacement, redevelopment, etc. The calculations should take into account the predicted number of such procedures during the service life.

The operational energy and water use (modules B6 and B7) are separated in the standard. These units take into account energy and water consumption and related emissions to meet the functional needs (e.g., maintenance of areas around the building, operation of integrated systems such as fountains and pools, etc.).

The end-of-life cycle stage is divided into four information modules which include energy consumption and carbon emissions from deconstruction or demolition (C1), including buildings in the surrounding area; waste transportation (C2) from the site to the processing plant or the landfill; the processing of waste (C3) at the relevant factory for reuse, recycling, energy production, etc.; final disposal (C4) which includes the necessary pre-treatment and disposal of waste, as well as monitoring and regulation of the waste management process.

The potential positive impact of the reuse and recycling of building waste, its components, and materials is taken into account in the additional information module which is not related to the life cycle of the object (D).

Life cycle carbon footprint results are reported as CO2 equivalent (kgCO2e) for each stage.

3. Methodology of carbon footprint assessment

The object of evaluation is the building and the site on which it is erected. The components of the building, including its foundations and external works, depending on the available data can be divided into the following components for the assessment:

– components of the preparatory cycle (construction site preparation, courtyard roads, and pavements, landscaping, etc.)

– substructure (foundations, retaining walls, etc.);

– elements of the above-ground cycle – load-bearing elements of the frame (columns, beams), floors, roof, stairs, elevator shafts, diaphragms and rigidity cores, external and internal walls and partitions, windows and doors);

– interior and exterior finishing;

– engineering and technical networks and equipment (heating, ventilation, air conditioning; sewerage systems; electrical and Internet networks).

– finishing works on the construction site (arrangement of courtyard roads and sidewalks, landscaping works)

– maintenance of technical condition (monitoring of technical condition, repair and renovation of building structures, repair work on existing systems, etc.).

The initial information about the building should include the purpose of the building (for example, office, residential, sports complex, etc.); total area; mode of operation (the number of people in the building at the same time; duration and frequency of stay; service life of the building).

For a building that consists of a certain number of elements, the carbon footprint of emissions throughout the life cycle can be determined by the formula:

$$CF = CF_{A1-A3} + CF_{A4-A5} + \\ + CF_{B1-B7} + CF_{C1-C4} - CF_D, \quad (1)$$

where CF is the building life cycle carbon footprint; CF_{A1-A3} is the pre-operational stage carbon footprint; CF_{A4-A5} is the construction and installation stage carbon footprint; CF_{B1-B7} is the operational stage carbon footprint; CF_{C1-C4} is the end-of-life stage carbon footprint; CF_D is the beyond life cycle carbon footprint.

Each component in formula (1) is defined as the sum of estimated emissions for building elements for each information group according to Table 1:

$$CF_{A1-A3} = \sum CF_{A1-A3,i}\ , \quad (2)$$

$$CF_{A4-A5} = \sum CF_{A4,i} + CF_{A5}\ , \quad (3)$$

$$CF_{B1-B7} = CF_{B1} + \sum CF_{B2,i} + \sum CF_{B3,i} + \\ + \sum CF_{B4,i} + \sum CF_{B5,i} + \sum CF_{B6,i} + \sum CF_{B7,i}\ , \quad (4)$$

$$CF_{C1-C4} = CF_{C1} + CF_{C2-C3} + CF_{C4}\ , \quad (5)$$

$$CF_D = \sum CF_{D,i}\ , \quad (6)$$

where i is a particular component i = 1, 2, 3, etc.

At the first stage of the life cycle (Modules A1-3) the calculation of emissions during the extraction, transportation, and processing of the raw materials for all components of the building is performed. For this purpose, the components can be divided into "plain" which are mainly made of a single material (e.g., concrete, steel, wood), and "complex", which consist of different materials and elements (e.g., windows, doors, facade systems, solar panels).

Carbon footprint for "plain" elements is calculated by multiplying the mass of the material by the reduction factor:

$$CF_{A1-A3,i} = V_i \cdot \rho_i \cdot k_{mat,i}\ , \quad (7)$$

where V_i is the volume of the *i-th* material for the production of building components; ρ_i is the density of the *i-th* material; $k_{mat,i}$ is the material carbon emissions factor which reflects the carbon equivalent of the total emissions from raw material processing.

For "complex" elements the carbon emissions can be calculated using the data from the environmental declaration of the manufacturer's products or based on the data from a close analogue by introducing the appropriate transition coeficient:

$$CF_{A1-A3,i} = Q_i \cdot k_{red,i} \cdot k_{ref,mat,i}\ , \quad (8)$$

where Q_i is the quantity of the "complex" element (e.g., total area or volume); $k_{red,i}$ is the reduction factor to the reference element; $k_{ref,mat,i}$ is the reference element carbon emissions factor.

Carbon emissions during transportation from the manufacturer to the construction site (Module A4) are determined by multiplying the mass of the corresponding element by the transport distance and the conversion factor:

$$CF_{A4,i} = M_i \cdot L_i \cdot k_{tr,i}\ , \quad (9)$$

where M_i is the weight of the *i-th* element which should be determined taking into account possible losses or damages during transportation; L_i is the distance of transportation which is determined from the location of the production plant directly to the construction site (local, regional, national and international transportation paths should be considered); $k_{tr,i}$ is the carbon emissions factor according to the transport type.

The construction of a building (Module A5) is a complex process that involves a lot of machinery, equipment and other resources. To overcome this problem and simplify the assessment, the information for calculating the emissions within this module is taken from the data for similar projects:

$$CF_{A5} = A_{tot} \cdot k_{constr}\,, \tag{10}$$

where A_{tot} is the total building area; k_{constr} is the carbon emissions factor per m^2 of the total area of the reference building.

Certified software packages are mainly used to forecast carbon emissions during the estimated life of the building (module B1). However, for the preliminary design, the approximate data of similar reference projects may be used with the introduction of the appropriate coefficient:

$$CF_{B1} = V_{tot} \cdot k_{ref.pr}\,, \tag{11}$$

where V_{tot} is the total building volume; $k_{ref.pr}$ is the carbon emissions factor per m^3 of the total internal volume of the reference building.

The emissions from maintenance operations (Module B2) can be determined by the following formula:

$$CF_{B2,i} = n_m \cdot T_{op} \cdot Q_i \cdot k_{m,i}\,, \tag{12}$$

where n_m is the amount of maintenance operations per year; T_{op} is the design period of the service life of the building; Q_i is the amount of building components which need the maintenance operations (e.g., the total net area of windows or facades, etc.); $k_{m,i}$ is the carbon emissions factor for the maintenance operation of the *i-th* component.

Similarly, the calculations for the repair work (Module B3) can be performed using the following equation:

$$CF_{B3,i} = n_{rep} \cdot T_{op} \cdot Q_i \cdot k_{rep,i}\,, \tag{13}$$

where n_{rep} is the number of repair operations per year; $k_{rep,i}$ is the carbon emissions factor for the repair operation of the *i-th* component.

The estimation of the carbon emissions when replacing some elements or refurbishing the building will include emissions from the production (Modules A1-A3), transportation and installation (Modules A4 and A5) of the necessary materials:

$$CF_{B4,i} = n_{repl} \cdot (\sum CF^{repl}_{A1-A3,i} + \sum CF^{repl}_{A4,i} + \sum CF^{repl}_{A5,i})\,, \tag{14}$$

$$CF_{B5,i} = n_{refurb} \times \times(\sum CF^{refurb}_{A1-A3,i} + \sum CF^{refurb}_{A4,i} + \sum CF^{refurb}_{A5,i}), \tag{15}$$

where n_{repl}, n_{refurb} are the number of replacement and refurbishment operations during the service life of the building; $\sum CF^{repl}_{A1-A3,i}$, $\sum CF^{refurb}_{A1-A3,i}$ are the total emissions from the production of necessary materials for replacement or refurbishment; $\sum CF^{repl}_{A4,i}$, $\sum CF^{refurb}_{A4,i}$ are the total emissions from the transportation of necessary materials for replacement or refurbishment; $\sum CF^{repl}_{A5,i}$, $\sum CF^{refurb}_{A5,i}$ are the total emissions from the installation of necessary materials for replacement or refurbishment.

The total amount of emissions at the end of the life cycle is determined by the formula:

$$FC_{C1} = A_{tot} \cdot k_{dem}\,, \tag{16}$$

$$FC_{C2-C3} = (M_{w,r} + M_{w,lf}) \cdot L \cdot k_{tr}\,, \tag{17}$$

$$FC_{C4} = M_{w,lf} \cdot k_w\,, \tag{18}$$

where $M_{w,r}$ is the weight of the waste recycled or reprocessed; $M_{w,lf}$ is the weight of prohibited construction waste; L is the distance from the building site to the reprocessing factory or land fill; k_{dem} is the demolition carbon emissions factor; k_{tr} is the transport carbon emissions factor; k_w is the waste treatment and disposal carbon emissions factor.

The materials obtained by the reuse, recycling or reprocessing can be used beyond the life cycle of the considered object (e.g. in the construction of a similar building). Therefore, the following formula can be used to evaluate the benefits of the possible use of these materials (Module D):

$$FC_{D,i} = FC^{recycled}_{A1-A3,i}\,, \tag{19}$$

where $FC^{recycled}_{A1-A3,i}$ is the total carbon emission from the extraction, transportation and production of the *i-th* recycled material.

Conclusions

A method for the assessment of the carbon footprint of the building object during its life cycle was proposed. The methodology is based on the requirements and provisions given in the standard EN 15978 “Sustainability of construction works. Assessment of the environmental performance of buildings. Calculation method”, accepted in the countries of the European Union.

The analytical formulas were derived to estimate the carbon emissions at the stages of extraction, transportation, and processing of raw materials (Modules A1-A3), construction and installation process (Modules A4 and A5), operation, maintenance and repair (Modules B1-B7), and liquidation and disposal (Modules C1-C4). Besides, possible benefits related to waste recycling and reuse of building components and materials are taken into account (Module D).

The proposed method meets the modern requirements for sustainable development and the circular economy in the construction industry. Further improvements directed on the collection and systematization of a standard database on carbon emissions from manufacturers of construction products are necessary to develop and approve the relevant guidelines for the application of this method in domestic design practice.

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