RESEARCH ARTICLES

Environmental Impact of the Choice of Building Materials in the Context of Sustainable Development

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Abstract

The manufacture of building materials and components, the construction, use and demolition of buildings contribute to the generation of environmental effects such as soil, water and air pollution. The paper defines and synthesizes the impact categories that affect the environment, as well as the factors that cause the appearance of impacts, for the choice of optimal ecological building materials. An important problem is finding impact indices that describe the factors affecting the environment, whose value might be quantified. For this, the study was extended to the methods for the evaluation and analysis of the environmental effects of impact factors. The study performed allowed to synthesize the following impact categories taking into consideration the impact factors that occur during the life cycle of materials: natural resources, human health and risk, pollution due to emissions and waste. The impact factors were analyzed from the point of view of the impact level (geographical extension) and the possible magnitude of their value. This article describes a relatively easy method for the choice of the optimal material from a group of materials, taking into calculation the following impact criteria and categories: depletion of natural resources, environmental degradation, toxic substance emissions due to the energy consumed during the production, execution, exploitation and demolition processes, as well as the possibility of reusing waste.

Keywords: *building materials, environment, pollution, sustainable development*

INTRODUCTION

Industrial sectors, including the building sector, began to acknowledge the impact of their activities on the environment in the 1990s (Haapio and Viitaniemi, 2008). Designers and builders become increasingly sensitive to the wide spectrum of problems that affect the environment, but are confronted with a confusing number of possible actions and solutions.

The manufacture of building materials and components, the construction, use and demolition of buildings contribute to the generation of environmental effects such as soil, water and air pollution (Curwell and Fox, 2002).

In this context, an important stage in the study of ecological materials is impact analysis, which involves the evaluation of environmental effects, i.e. the passage from environmental impact factors to environmental impact proper.

Impact analysis is carried out in three stages:

- classification of impact factors;
- characterization of the effects of impact factors;
- evaluation of the weight of environmental impact.

CLASSIFICATION OF IMPACT FACTORS

A first method for the classification of impact factors was the ”critical volume” method, by which impact factors were classified depending on the physical environment in which they are eliminated: air, water and soil.

The classification of impact factors depending on their environmental effects becomes increasingly used. For example, the nitrogen oxides (NOx) eliminated in the air contribute to both the greenhouse effect and acidification.

Table 1 synthesizes the main environmental impacts of a product or process that can be considered, as well as their way of classification.

Tab. 1. Categories of environmental impact (Apostol and Ciucaşu, 2000)

Impact factors	Impact	Consequences	Area/ Impact Level
Category: Resources			
Energy and mineral resources exploitation	Reduction of non-renewable natural resources Abiotic depletion	Risk of exhaustion of natural resources. Degradation of the landscape in the case of overground mining. Landslides in the case of underground mining.	Global/ Major
Wood exploitation	Reduction of renewable natural resources Biotic depletion	Destruction of the natural habitat, with negative consequences on the flora and fauna. Negative influence on the natural water circuit, with consequences on the climate and extreme meteorological phenomena. Landslides.	Global/ Major
Water use	Reduction of water resources	Desiccation Destruction of the natural habitat, with negative consequences on the flora and fauna	Regional/ Major
Category: Human health and risk			
C_6H_6, C_6H_5Cl, CFC, H_2S, Pb, Hg, $CHCl_3$, C_6H_{14}, $(PO_4)^{3-}$, Zn, St, Cu	Human toxicity	The accelerated development of industry in all fields, including building materials, contributes to the increase of toxic agents.	Regional/ potential
C_6H_6, C_xH_y, C_2H_2, CH_4, C_6H_{14}	Oxidant formation	Formation of photochemical ozone in the troposphere (smog)	Regional/ potential
Number of cases	Victims	Undesired events resulting in the loss of human lives or severe injury	Local/ potential
Category: Pollution and waste			
CO_2, CH_4, N_2O, CFC	Global warming potential	Contribution to the global warming of the earth	Global/ potential
CFC_{11}, CCl_4	Ozone depletion	The reduced ozone layer density can no longer protect the organisms and plants from the noxious ultraviolet rays of the sun.	Global/ potential
SO_2, NO, NO_x, NH_3, HCl	Acidification	These factors contribute to a basic substance depletion of the earth's surface, whose acidity continuously increases. This process leads to soil and water degradation, as well as to the deterioration of ecosystems.	Regional/ potential
PO_4^{3-}, NH_4^+, NO_2, NO_x and Chemical Oxygen Demand	Nitrification	This effect translates into a high oxygen consumption in water and terrestrial environments, due to high nitrate and phosphate concentrations. The lack of oxygen leads to the reduction of the aquatic fauna and soil degradation.	Regional/ potential
C_6H_6, Cd, C_6H_5Cl, Pb, Hg, $CHCl_3$, Cr, Zn	Aquatic ecotoxicity Terrestrial ecotoxicity	Heavy metal and non-halogenated aromatic hydrocarbon emissions in water and terrestrial environments have toxic effects, degrading these environments.	Regional/ potential
[Bq]	Radiation	Irradiated victims	Local/ potential
[m^3]	Volume de dechets	Pollution of air, water and soil.	Regional/ potential

The table classifies impact factors depending on:
- geographical extension (global, regional or local);
- categories of effects (resources, human health and risk, pollution due to emissions and waste, discomfort and others);
- size of the value (absolute or potential).

EVALUATION OF THE WEIGHT OF ENVIRONMENTAL IMPACT

The impact analysis of building materials requires the determination of the value of impact factors that appear along the life cycle of these and the assessment of the weight of the impact of various materials.

Methods for the evaluation of impact factors (Badea et al., 2004)

1. Exhaustion of natural resources

The exhaustion of natural resources can be described by means of three parameters: the consumption of raw materials (M), the contribution to the exhaustion of natural resources (T), and the degree of regeneration of raw materials (R).

The consumption of raw materials (M) is calculated using the relation:

$$M = \Sigma m_i \text{ [kg/functional unit]}$$

m_i – mass of consumed raw material *i* [kg/functional unit].

The contribution to the exhaustion of natural resources (T) is calculated using the relation:

$$T = \frac{\sum_i m_i \times \frac{1}{a_i}}{M} \text{ [an}^{-1}\text{]}$$

T – contribution to the exhaustion of natural resources [year^{-1}];
a_i – abundance of raw material reserves *i* [year];
M – consumption of raw material [kg/functional unit].

T ranges between 0 and 1 year^{-1}, which corresponds to a null or total contribution of the system to the exhaustion of natural resources.

a_i is the ratio between the status of reserves and the annual international consumption of raw material i.

The degree of regeneration of raw materials (R) is evaluated starting from the relative time of regeneration of raw materials ”t”. This index represents the time of regeneration of raw materials in relation to the biomass taken as a reference for t = 1. Fossil materials such as coal, oil and natural gas have a regeneration time at least 100,000 times higher compared to that of the biomass, while the regeneration time of uranium is practically infinite.

The degree of regeneration of raw materials R is calculated using the relation:

$$R = \frac{\sum_i m_i \times \left(1 - \frac{1}{t_i}\right)}{M}$$

R – degree of regeneration of raw materials;
t_i – relative time of regeneration of raw materials in relation to the time of regeneration of the biomass taken as a reference;

R varies between 0 and 1, which means a total or null regeneration of the raw materials consumed by the system.

2. Degradation of the landscape

It is relatively difficult to develop a method for evaluating the degradation of the landscape. A variant would be the scoring method, by which penalties and bonuses for the rehabilitation of the considered space are attributed.

Thus, four levels of degradation of the landscape are defined:
I – natural systems without any human intervention;
II – there is a human influence on the initial flora and fauna, but no cultivated surfaces are present;
III – the majority of the space is cultivated;
IV – urbanization is predominant (highways, buildings, etc).

The passage from a lower to a higher degradation level is materialized by a penalty (P), while the rehabilitation of an area (passage from a higher to a lower degradation level) is rewarded by a bonus (Tab. 2).

Tab. 2. Application of penalties and bonuses for urbanism areas (Badea *et al.*, 2004)

Degradation	Penalties	Rehabilitation	Bounty
I → II	4	II → I	0,25
II → III	3	III → II	0,33
II → IV	4	IV → II	0,25
III → IV	2	IV → III	0,50

Tab. 3. Impact indices in the CML method (Badea *et al.*, 2004)

Categories of impact	Impact indices	Units of measurement
Global Warning Potential	GWP	Kg CO_2 equivalent
Ozon Depletion Potential	ODP	Kg CFC_{11} equivalent
Nutrification Potential	NP	Kg PO_4- equivalent
Acidification Potential	AP	Kg SO_2 equivalent
Photochemical Ozone Creation Potential	PCOP	Kg C_2H_4 equivalent
Human Toxicity	HT	Relative to human body kilograms
Ecotoxicity aquatic Ecotoxicity terrestrial	ECA ECT	m^3 polluted water kg polluted soil
Abiotic Depletion Potential	ADP	-

Penalties are subject to the following rules:

- the higher the degradation, the higher the penalty;
- the closer to the natural state the considered area initially is, the higher the penalty for its degradation.

Impact is calculated using the relation:

$$I = S \cdot P \cdot d \ [m^2 \cdot year]$$

S – the occupied surface, in [m^2];

P – the penalty corresponding to Table 2;

d – the duration of occupation of the space in years.

3. Atmospheric emissions

This method involves the analysis of the effects of impact factors (e.g.: nitrogen oxides induce the acidification of the atmosphere, which causes acid rain with negative effects on vegetation). For a good quantification, the connection between emission – dose – effect should be analyzed: emission (nitrogen oxides) – dose received by the receptor (vegetation) – effect of this dose on the receptor (effect of the amount of nitrogen oxide on vegetation).

In order to analyze the effect of impact factors, this should be quantifiable.

Table 3 presents the impact indices in the CML method and the measurement units by which these are defined (Ojoawo and Gbadamosi, 2013).

For different gases, GWP is expressed compared to GWP relative to CO_2, which means that the instantaneous emission of 1 kg gas is compared to the emission of 1 kg carbon dioxide taken as a reference, whose global warming potential is considered equal to the unit.

Table 4 presents the GWP values of the main gases with a greenhouse effect, for the warming periods of 20, 100 and 500 years.

In calculations, the shortest time period is usually considered, i.e. the 20 year period.

The GWP index for a system is determined by adding up the elementary greenhouse effect potentials of all gases in the composition of the gaseous effluent of the system, multiplied by the amount corresponding to each component:

$$GWP = \sum_i m_i \times GWP_i$$

GWP_i – the greenhouse effect potential of element i of the gaseous effluent [kg CO_2 equivalent];
m_i – the amount of element i [kg/functional unit].

The most widely used acidification indicator is equivalent acidity compared to SO_2, determined by the relation (Răducanu *et al.*, 2004):

$$AP = \sum_i m_i \times AP_i$$

AP_i – the acidification potential of a substance i;
m_i – the amount of element i [kg/functional unit];
AP – the acidification potential [kg SO_2 equivalent/ functional unit].

The AP values of a substance are given in Table 5.

In order to enable the comparison of the results of different studies on the life cycle analysis of materials, the UCPTE model for the production of electricity was created at European Union level (Badea *et al.*, 2004), for which the emission amounts m_i expressed in mg/kWh, were established.

ANALYSIS OF THE IMPACT OF BUILDING MATERIALS USING THEIR QUALITATIVE ASSESSMENT

The analysis involves the choice of the ecologically optimal material of the foundation materials category.

In this analysis, the following scores are established, which express the adequacy of the choice depending on the impact factors of the material: 0 – to avoid; 1 – unrecommended, because of major disadvantages; 2 – recommended, although having some small disadvantages; 3 – recommended, ideal.

The best material will be considered the material that accumulates the highest score resulting from the arithmetic mean of the scores given to effects.

Tab. 4. GWP values for the main gases with a greenhouse effect (Apostol and Ciucaşu, 2000)

Substance	GWP_i (20 years)	GWP_i (100 years)	GWP_i (500 years)
CO2	1	1	1
CH4	35	11	4
N2O	260	270	170

Tab. 5. AP values of some substances (Apostol and Ciucaşu, 2000)

Substance	AP_i
SO_2	1,00
NO	1,07
NO_2	0,70
NO_x	0,70
NH_3	1,88
HCl	1,88
HF	1,60

Tab. 6. Technical data

Material	Density	Thermal Conductivity	Specific Heat
	kg/m³	W/(mK)	J/kgK
Stone	2180	1,5	720
Brick from demolition	1500	0,85	840
Concrete	2400	2,2	840

Tab. 7. Fundamental data useful from an ecological point of view

Material	Embodied energy	CO_{2eq}	SO_{2eq}	Lifetime
	[kWh/kg]	[g/kg]	[g/kg]	[year/material]
Stone	0,36	88	0,33	100
Brick from demolition	0	0	0	50
Concrete	0,22	132	0,46	80

Tab. 8. Evaluation of environmental efects along the life cycle

Life cycle stage	Impact factors	Impact	Unit of measurement	Material		
				Stone	Brick from demolition	Concrete
Raw material	Consumption of raw materials	Depletion of natural resources	[kg]	2180	0	2400
			[kv]	2	3	1
	Excavation	Landscape degradation	Level	II	I	II
			[kv]	2	3	2
	Total assessment [kv]			2	3	1,5
Production	Embodied energy	Environmental degradation	[kWh/m³]	784,8	0	528
			[kv]	1	3	2
	Environmental effects	Greenhouse effect	CO_{2eq} [g/m³]	191840	0	316800
			CO_{2eq} [kv]	2	3	1
		Acidification	SO_{2eq} [g/m³]	719,4	0	1104
			SO_{2eq} [kv]	2	3	1
	Total assessment [kv]			1,66	3	1,33
Construction	Embodied energy	Environmental degradation	[kWh/m³]	0	0	0
			[kv]	3	3	3
	Harmful emissions	Environmental effects	-	0	0	0
			[kv]	3	3	3
	Total assessment [kv]			3	3	3
Operating	Energy – Maintenance	Environmental effects	[kv]	n.s.	n.s.	n.s.
	Energy – Use		[kv]	n.s.	n.s.	n.s.
	Thermal comfort	Health effects	[W/(m K)]	1,5	0,85	2,2
			[kv]	2	3	1
	Harmful emissions	Environmental effects	[kv]	n.s.	n.s.	n.s.
	Total assessment [kv]			2	3	1
Demolition / waste	Energy	Environmental effects	[kv]	2	3	2
	Recycling +/–		[kv]	2	3	1
	Total assessment [kv]			2	3	1,5

Tab. 9. Ecological evaluation

	Stone	Brick from demolition	Concrete
Quality Rating [kv]	2,13	3	1,66
Ranking (position)	2	1	3

The materials were analyzed during their life cycle, from the raw material to the demolition/ waste stage, assuming that the functional unit was $1m^3$. The functional unit provides a means of comparing different materials/ products or designs for a given function (Shrestha *et al.*, 2014).

Scores were given depending on the effect values, so that negative effects received the minimum value.

The sources of the data used are from the literature (Hammond and Jones, 2011; Reardon *et al.*, 2011; Takano *et al.*, 2014).

The technical data of the materials included in the study are presented in Table 6.

In the present case, the best foundation material from an ecological point of view is brick from demolition.

CONCLUSION

In the presented analysis, it can be noted that the environmental impact of materials manifests during all life cycle stages.

An important observation is the fact that energy is an important impact factor which, although evidenced only in some of the life cycle stages of materials, is present during their entire life cyle. This is supported by the fact that each of the presented life cycle stages are based on energy used for their manufacture as well as energy due to transportation during and between the different stages. Thus, the embodied energy of materials is a particularly important impact factor, whose effects should be given special attention in the analysis of ecological materials.

Advantages of the method: it is relatively simple, it considers the environmental effects along the entire life cycle of the product, it is practical – it provides the designer with clear and accurate information on the best material from an ecological point of view.

Disadvantages of the method: the qualitative value kv is subjective, the weight of the studied factors is not taken into consideration; although a practical and useful method in designing, it has the disadvantage that it cannot be applied to new materials available on the market, unstudied materials or materials for which no data regarding their environmental effects are available.

In the study and choice of ecological materials, impact analysis is particularly important, but no methodology is currently unanimously accepted by specialists in the field.

The evaluation of the environmental effects of building materials and the finding of reasonable synthetic indices to express the environmental impact represent an open problem of major importance.

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