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MULTI-ATTRIBUTE ANALYSIS FOR THE ECO-ENERGETIC ASSESSMENT OF THE BUILDING LIFE CYCLE

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Abstract. In the recent years, attention has been attracted to the development of activities (developing and implementation of standards, directives, regulations, policies etc.) related to the environmental protection and implementation of the principles of sustainable development. Also in Poland, principles of that concept are put into practice. There is, however, a shortage of elaborations which the future investor or designer could, in an easy way, utilise for the selection of environment-friendly materials, technologies, building utilities and so forth, i.e. to design a facility which causes the least harm possible to the environment, maintaining at the same time low energy demand during its life cycle. According to the philosophy of environmental protection, a building design should take into consideration its entire life cycle, and its structure and utilities should allow the supplies of energy needed for heating to be eliminated while using the building. The present paper aims to give multi-attribute analysis for assessment of building variants, which utilises the Life Cycle Assessment method (LCA). The method defines a number of so-called environmental impact categories, which include criteria to be considered while selecting a solution, which minimises such impacts. The most important of them and costs are taken into account in the multi-criteria analysis for optimum solution selection. The results of eco-energetic assessment of variants house are grounds to supporting decisions in programming, designing and performing houses, taking into consideration numerous others aspects (usable, technical, social etc.).

Keywords: sustainable development, LCA method, multi-criteria analysis, optimization, design support method.

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1. Introduction

A great number of factors can be used to valuate a building. Factors' selection depends on a purpose of this assessment (e.g. Norris and Marshall 1995). It can be: select the best building component, select the best residence, or select the best building location and others (Fig. 1).

These selections are based on the analysis of many attributes and their hierarchy. This paper aims to make an eco-energetic estimation of a building that is characterized by groups of the factors presented on Fig. 1. Firstly, environmental impacts will be defined and analyzed. The estimation regards materials and building installations. The choice of appropriate materials is very important, because production of building materials, construction of building structures and their further use constitutes, in general terms, a source of detrimental effects on the environment. The eco-energetic assessment requires taking into consideration a building life-cycle. The knowledge on the ecological assessment of a building life cycle should be utilised while making a decision on the selection of types of materials available, production technologies, selection of material, structural and utilisation solutions in buildings by the designer and, most importantly, by the investor. Such choices, regarding the designer and investor, are obviously influenced by regulations, standards, competition etc., whereas the investor-user relationship is affected by the social awareness of the necessity to observe the rules of sustainable development, project economics spread all over the building life cycle, and regulations being introduced, related, for example, to energy certification of buildings. There is, hence, a demand for a simple tool to design and decide the solutions for buildings to meet the relevant requirements.

The detrimental environmental impacts can be assessed and determined with a variety of methods. One of them being LCA – Life Cycle Assessment. This method allows harmful environmental factors to be identified together with the points of strongest effect on the environment throughout the entire life cycle, and to compare alternative products and production technologies.

One of the issues of the strategy of sustainable development, also as regards the building sector, is to minimise energy consumption during the production of building materials, erection of buildings and during their life cycle. According to the analysis of harmful environmental factors present during the production and use of the products (e.g. buildings),

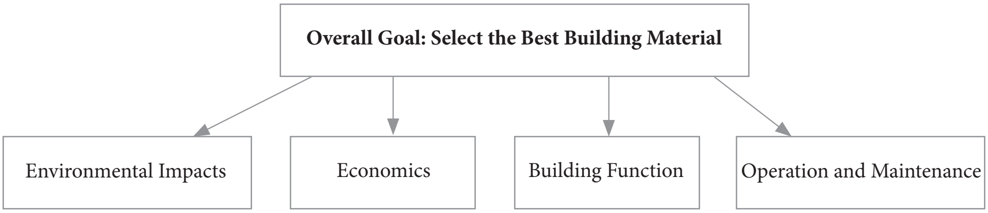

Fig. 1. An example hierarchy for the problem of selecting a building material

the majority of them are the derivatives of energy acquired from combustion of fossil fuels (greenhouse effect, acidification, toxicity etc.). Although this is the greenhouse effect that prevails during the building utilisation stage, the other factors, identified as the environmental impact categories, prevail during the production stage (toxicity).

The concept of supporting the decision-making during the design stage, and while deciding an optimum solution, as presented in this paper, is based on the LCA method and on the multi-criteria optimisation based on the Baas-Kwakernaak method (Bass and Kwakernaak 1977). As an example, it has been utilised to evaluate material solutions of a single-family house. Single-family buildings have a considerable share in the general building production and are of critical influence on the degradation of environment. More than 40% of Polish citizens live in single-family houses, and use fossil fuels for heating (coal, gas). In the multi-criteria analysis, the environmental impact categories have been adopted as the optimisation criteria, related to the consumption of energy generated by combusting fossil fuels.

2. Subject of studies in view of literature

In the view of the literature two problems are considered: the application of multi-attribute analysis for investigations and valuation of building questions and a problem of eco-energetic valuation of buildings – how do they influence environment in dependence on the implemented constructional solutions.

For instance, multi-attribute decision analysis methods (MADA) for evaluating buildings and building systems are presented in a voluminous publication (Norris and Marshal 1995). This report reviews 14 classes of methods for performing MADA. It summarizes their usefulness for screening, ranking, and choosing among projects; their data input requirements; and how each method scores project alternatives. Two methods: the analytical hierarchy process (AHP) and non-traditional capital investment criteria (NCIC) are described in detail. Assumptions, procedures, strengths, and limitations are described for each. Detailed descriptions of some typical building-related decisions – choosing among office buildings, residences, building components, and building materials-provide additional examples of possible MADA applications. A list of 15 building-related attributes with complete definitions helps decision makers customize a MADA model for making a building choice. Although the report focuses on buildings, MADA methods apply equally to the evaluation of non-building capital budgeting decisions.

The multi-attribute analysis in building is useful for investigation and solving different types of questions – more or less particular. It is being employed for examination and decision-making in building construction projects (Zavadskas *et al.* 2007; Zavadskas *et al.* 2008; Ginevičius *et al.* 2008), building objects' localization (Zagorskas and Turskis 2006), as well as for building implementation management. Many works present an application of the multi-attribute analysis for investment risk estimation in construction (e.g. Shevchenko *et al.* 2008), estimation and choice contractors (Turskis 2008; Turskis *et al.* 2009; Zavadskas and Vilutienė 2006; Jaselskis and Russell 1992; Zavadskas *et al.* 2008).

In multi-attribute analysis different computational methods are used and developed, starting with these generally known, as ELECTRE, AHP (Saaty 1988), up to the newest – Clara and Saw (Shevchenko *et al.* 2008), and many others (Bass and Kwakernaak 1977; Trzaskalik 2008).

In this paper the problem of influence of a building object for environment is analyzed with the multi-attribute analysis. This influence means emitting a lot of toxic compounds arising during building materials production, and especially caused by heating. Related to this problem is defining and rating criteria for ecologic and energetic evaluation of the building. There is an extensive literature concerning different aspects of "building object-versus-environment" relation.

We can mark out some groups of examined problems:

- Examination and analysis of environment's encumbrance caused by raw and building materials in life-cycle (Gorzynski and Piasecki 2002; ISO 14040÷42; European Environment Agency 1997).
- Rankings of materials, considering environment's encumbrance (The Handbook ... 1996).
- Studies on selected elements, structures and buildings, according to toxic compounds emitting (Seo and Hwang 2001; Piasecki 2003; Stachniewicz 2006; Giergiczny 2008; Stephan and Wilhelm 2006; Odeen *et al.* 1996).
- Projecting of energy-saving and passive buildings to minimize fossil-fuel energy consuming, during exploring them as a warmth providers (Brandt 2005; Sarosiek and Sadowska 2006; Stachniewicz 2006; Szczechowiak 2008).
- An energetic validation of buildings (EPBD 2003).

The studies indicate that, bearing in mind the building life cycle, the greatest environmental impact in most categories is present during the period of building use, due to the need for heating in winter in our climate and in most EU countries. Therefore, the development of energy-saving and environment-friendly building technologies is supported by the EU directives and relevant regulations, e.g. CPD – Council Directive 89/106/EEC (CDP 1989) and EPBD – Parliament and Council Directive 2002/91/EC (EPBD 2003), on the energy performance of buildings.

The CPD Directive is the basic document relating to the construction products and building industry in the European Union. It introduces, among others, the assessment of suitability of construction products for the intended use. The Directive sets out the requirements regarding the materials and products used in terms of: (1) load-carrying capacity and stability, (2) fire safety, (3) health and hygiene, (4) safety of use, (5) noise protection, (6) energy saving and thermal protection in properly designed and constructed buildings (additional new requirement relating to environmental protection according to the sustainable development principle).

The EPBD Directive introduces the requirement of an obligatory energy-certification of buildings, which should be designed and constructed in such a manner that the energy required for their use is kept at a low level, taking into consideration the local climatic conditions and needs of the residents. The energy-quality of a building should also include the quality of the internal environment and economic efficiency. Provisions of the Directive are supposed to come into force in the EU states in 2009 the latest. The mentioned directives support the development of low-energy and passive buildings and as a consequence lead to significant decrease of environmental degradation by building production and usage.

3. Research methodology

With a variety of producers of building materials, indoor system solution (heating, water heating, ventilation heat recovery system), building erection technologies, it is possible to design and construct different variants of buildings. They are of varied impact on the environment along their entire life cycle, and the relevant knowledge should be used on the design stage, while making decision on the choice of a given material and construction solution for the building. The building design is expected to meet the requirements related to the environmental protection and of both, the investor and user. Fig. 2 presents the concept of the IT system supporting designing of buildings of various material, construction and indoor systems solutions, their valuation from the point of view of the environmental impact categories, namely the emission of pollution, and finding with the multi-criteria analyses an optimum solution meeting the minimisation criteria adopted. The decision as to the choice of a given variant analysed throughout the entire life cycle should also take into consideration the advance in technology and its scenarios during prolonged use of the building.

The proposed method is, therefore, based on the determination of ecological and energetic characteristics of a structure of improved inherent energy economy and energy delivered. In this method for designing buildings, taking into consideration their influence on the environment, the decision is made after the completion of three stages of the research and design work:

- Determining the environmental impact of the building with the LCA method.
- Select and choice attributes to multi-criteria analysis.
- Drawing up an optimisation balance
- Choice variant and possibly re-designing the chosen variant into a building of low energy demand (green house).

Stage 1 involves designing the version of a building, so-called "basic", and other versions using database on materials and their influence on the environment. Proposed variants with selected plumbing and heating systems are subjected to assessment with the determined/calculated vectors of environmental impact, according to the LCA method.

The LCA method is described in the ISO 14040÷42 standards. The method defines and evaluates a set of inputs and outputs of the product system, and its influence on the environment throughout the entire life cycle. The streams of inputs and outputs, and their material and energy balance, determine arduousness of the product to the environment. The LCA analysis involves a selection of the "environmental impact categories" which determine the influence of substances polluting the environment. The obtained data on the emission, consumption of resources and others, are grouped according to their categories, and then subjected to aggregation for easier interpretation of the results. The result of the study is an environmental characteristics of the product in a form of a multi-dimensional vector of environmental impacts Ω. The method for calculation the Ω vector is described in ISO 14040.

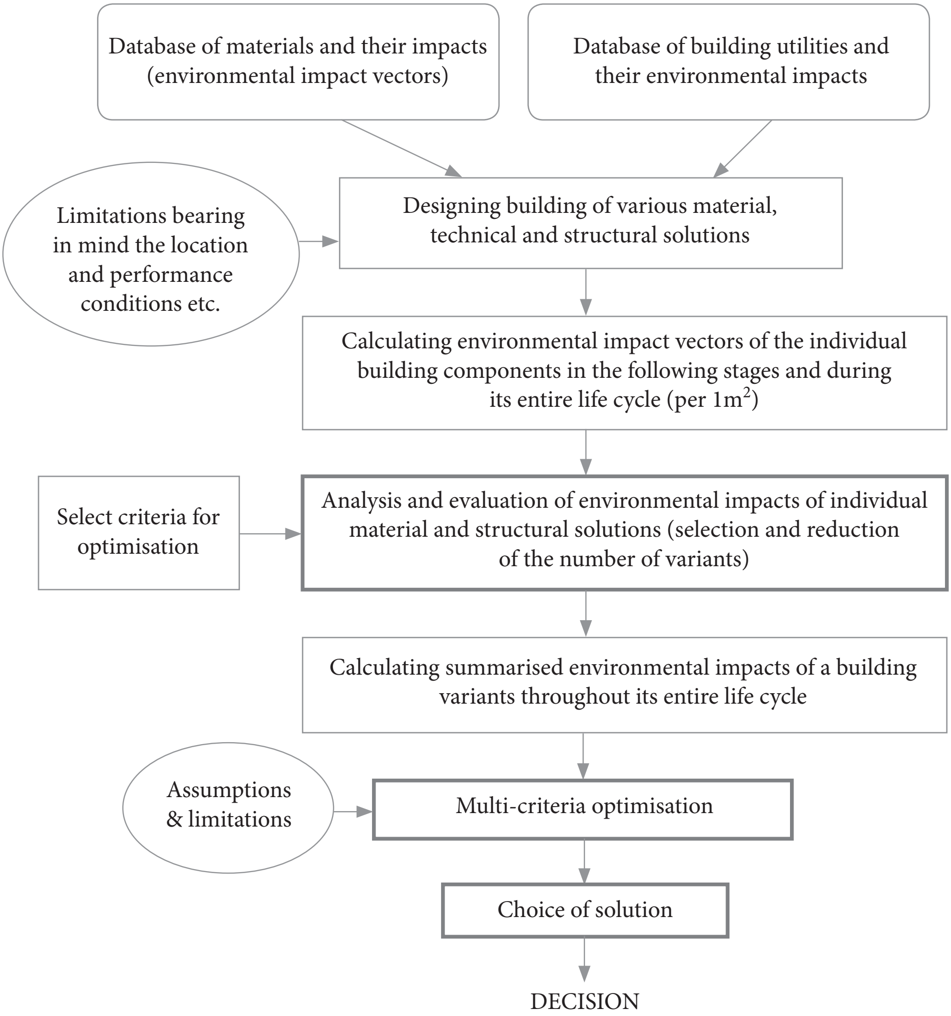

Fig. 2. Sequence of actions to be taken

An equivalent emission of pollution in a given category can be expressed with the general formula (Gorzynski and Piasecki 2002):

$$\Omega_x = \sum_{j=1}^{n} b_j m_j , \qquad (1)$$

where: b_j – an equivalent environmental impact for an i^{th} reference substance, m_j – mass of the i^{th} substance released to the environment in the discussed group of pollutants kg subst./kg, n – number of substances in a given impact category included in the analysis, x – denotes given criterion.

To each material contained in the product, a set of equivalent cumulated environmental impacts Ω_i can be assigned, including impacts in individual categories in a form of a k-dimensional vector:

$$\Omega_i^T = \left[\Omega_e, \Omega_z, \Omega_w, \Omega_b, \Omega_c, \Omega_a, \Omega_f, \Omega_{eu}, \Omega_l, \Omega_{htp}, \Omega_{htw}, \Omega_s, \Omega_t\right], \tag{2}$$

where: e – cumulated consumption of primary energy, z – cumulated consumption of non-energy resources, w – cumulated water consumption, b – index of cumulated emission of greenhouse gases, c – index of cumulated emission influencing the atmospheric ozone, a – index of cumulated acidifying emission, f – index of cumulated emission triggering photochemical oxidisation, eu – index of cumulated emission of eutrophic action, l – eco-toxicity, htp, htw – indexes of cumulated toxic emission in ambient air and in water surrounding, s – generation of solid waste, t – transport.

Each environmental impact category is described by a set of equivalent emissions of substances causing a given environmental effect. One type of pollutant can influence several impact categories with various equivalents. Most units used in the environmental criteria are of equivalent character, for example:

- Greenhouse effect [kg CO_2 eq./100 l] refers to the emission, in a 100-year period, of carbon dioxide and other substances affecting the greenhouse effect, “transformed” into CO_2. These are the methane, nitrogen suboxide, sulphur hexafluoride and others;
- reduction of the ozone layer [kg CFC11eq.] caused by substances acting on the atmospheric ozone;
- acidification [kg SO_2 eq.] with sulphur dioxide and nitrogen oxides, ammonia and other acidifying substances;
- toxicity to human – air [kg tox.] refers to the emission of kgs of toxic substances: acetone, acetylene, aromatic hydrocarbons, carbon benzenoxide, dioxins, ethane, heavy metals, nitrogen oxides, sulphur dioxide, xylenes and a number of other toxic substances in ambient air;
- toxicity to human – water [kg tox.] refers to the emission of kgs of toxic substances in water: aliphatic and aromatic hydrocarbons, heavy metals, pesticides and others;
- photochemical smog [kg ethene eq.] caused by ehtene, acetone, acetylene, butanols, benzene, ethane, formaldehyde, glycols, propane, toluene, xylenes and many other compounds resulting in photochemical oxidisation per one kg ethane;
- eco-toxicity [m^3] refers to air pollution by 1 mg of toxic substances such as: heavy metals, dioxins, pesticides, others;
- eutrophisation [kg PO_4 eq.] caused by phosphate and nitrogen suboxide, ammonia, nitrates and orthophosphates ions etc. released to water, expressed in kg PO_4.

Impact vectors for building materials which are analysed in this paper, based on the data obtained from the Building Research Institute, professional literature and building materials producers. Bearing in mind the data, regarding the emission of individual materials and products for a specific building design, it should be transformed into a unit of a component, in relation to the entire life cycle (production, construction, use and disposal).

The LCA method does not assume further aggregation of individual environmental impact categories for a given product, yet attempts are also made to prioritise individual criteria, in order to find the best (optimum) solution. The necessity of such actions results from the difficulties in interpretation of data obtained from the LCA analysis. It is, therefore, necessary to carry out a multi-criteria comparison analysis, in order to choose the proper solution. Such analysis, along with the selection of poly-optimisation criteria, is the second and thirty stage of the studies involved in the concept of design support. The task involves poly-optimisation activity, the criteria of which are the chosen environmental impact factors (categories). Presenting the results in a single number, expressing the environmental impact according to the criteria adopted allows solution variants to the compared according to such criteria and to find a compromise between them. In the proposed system for the selection of an optimum solution, various poly-optimisation methods can be adopted, e.g. the traditional ones: Weighted Objectives Method, Utility Function Method, or the modern ones using evolutionary algorithms (Jaskowski and Sobotka 2004). In the example discussed, the Baas and Kwakernaak (Nikiel 2004) method using fuzzy assessment has been utilised due to the fact that some of the assessments in the model have the properties of fuzzy values (example of mass – see 4.2).

4. Application example

4.1. Calculating the environmental impact vectors

The proposed methodology for designing and selection of the material and construction variant of the building is presented based on an example of a design of a single-family house and selection of an optimum solution from the point of view of minimisation of the environmental pollution throughout the entire life cycle.

This section covers the results of studies of a building designed in four material and structural variants (Table 1). The data collected and calculations performed allow creating considerably a greater number of variants, yet the studies were limited to typical solutions. The basis for the elaboration of the variants, is the design of a one-storey, single-family house with partial basement, of gross covered area 195.0 m^2, heated area of 200 m^2, heated cubage of 568 m^3, A/V index = 0.35 kW · h/m^3 year, and the seasonal heat demand 53.1 kW · h/m^3 year (150.9 kW · h/m^2 year), here referred to as the basic variant. The building has an unheated, glazed veranda on the north side, serving as an entrance enclosure, and a timber terrace and cellar on the southern side. The heat transfer coefficient for the walls of the building in the basic variant (and others) is 0.29 W/(m^2 K). In all building versions tested, an identical heating system has been adopted.

The assessment involves the comparison of the environmental impacts of the individual components and of the building as a whole. The following parts were assessed: external walls, ceiling above the ground floor, roof covering, windows. Other components were categorised in individual material groups and calculated in relation to the entire building.

Table 1. The list of residential building variants

Variant	Description
P – basic	external walls of YTONG cellular concrete blocks, timber floor, ceramic roof tiles, wooden window joinery.
C – ceramic	double-leaf walls of MAX hollow bricks, insulation with lightweight wet method with Styrofoam, CERAM 45 rib-and-slab floor, ceramic roof tiles PVC window joinery.
G – cellular concrete blocks	three-leaf walls of cellular concrete 600, insulated with rockwool, solid reinforced concrete floor, sheet metal tile roofing, wooden window joinery – as in the basic version
D – timber	walls – timber framework, wooden sheathing, with rockwool filling, timber floor as in the basic version, sheet metal tile roofing, wooden window joinery.

The environmental impacts were studied in the following sequence:

- collecting data on the environmental impact vectors Ω regarding the unit quantities of individual materials built-in the structure;
- calculating values of the environmental impact vectors in individual and in the entire life cycle of the building per 1 m^2 of a wall (see Table 2), floor, roof and window (see Table 3);
- calculating the environmental impact vectors for the life cycle of the building (see Table 4);
- analysing the results and conclusions (assessment of building variants).

The analysis involves the following stages of the building life cycle: 1 – building, comprising stages: acquisition of raw materials, production of products, leaving the factory, transport from the factory to the building site, construction of the building, 2 – use of the building (component), 3 – demolition. The basic assumptions of the calculations:

- averaged industrial data on the emission and other environmental impacts were adopted;
- according to the LCA methodology, in the analysis from material acquisition to the completion of construction, the influence of partition components below 2% of its mass was omitted (paint, nails etc.);
- masses of components were assumed based on the producers' data or the PN-82/B-02001 standard;
- the building is located in the 3rd climatic zone (Krakow, latitude 50°);
- the transport work, including delivery of the material from manufacturers to the construction site, were adopted pro rata to the partition mass (around 2 tons/km in case of wall partitions (Piasecki 2003);
- during the construction phase the following was assumed: a concrete mixer capacity 250 l to prepare masonry and plaster mortars, motor power rating 1.1 kW; a hoist lifting capacity 0.5 t for vertical transport; (1.1 kW); delivery of material to the site – close to the place of use;

Table 2. Values of environmental impact vectors in the whole life cycle of a wall per 1m^2

Environmental impact categories	Variants of walls			
	P	C	G	D
Greenhouse effect, kg CO_2 eq./ 100 year/unit	389	544	425	223
Reduction of the ozone layer, kg CFC11 eq./unit	7.48E-05	7.43E-05	7.75E-05	7.41E-05
Acidification, kg SO_2 eq./unit	0.62	1.67	0.73	0.80
Toxicity to human – airborne, kg toks./unit	2.04	3.20	2.26	2.28
Photochemical smog, kg etene eq./unit	0.12	0.29	0.14	0.10
Primary energy, MJ/unit	13,682	14,984	13,936	13,659
Toxicity to human – water, kg tox./unit	0.064	0.061	0.075	0.050
Eco-toxicity, m^3/unit	9,452	54,869	9,717	27,197
Eutrophisation, kg PO_4 eq./unit	0.090	0.422	0.109	0.104
Mineral use, kg/unit	304	711	490	138
Water, l/unit	4,513	5,081	4,667	5,113
Waste, t/unit	6.33	7.22	6.62	6.06
Transport, t · km/unit	7.05	21.44	12.56	5.08
Cost* of 1 m^2 component-wall, [PLN]	984	1 088	744	942

* own estimating (according to Polish Standards of Construction Works Cost Estimating 2005), it inclusive whole-life cost (WLC).

Table 3. Values of environmental impact vectors in the whole life cycle of a floor, roof and windows per 1m^2

Environmental impact categories	Variants floors			Variants roofs		Variants windows	
	timber	ceramic	reinforced concrete	ceramic roof tiles	sheet metal roof tiles	wood-aluminum window joinery	PVC window joinery
Greenhouse effect, kg CO_2eq./100year/unit	–91	136	105	–49	–29	899	947
Reduction of the ozone layer, kg CFC11 eq./unit	3.24E-06	3.49E-06	3.25E-06	9.57E-08	6.42E-10	0.92	0.91
Acidification, kg SO_2 eq./unit	0.35	0.89	0.56	0.29	0.10	2.22	1.18
Toxicity to human – airborne, kg toks./unit	0.86	1.39	0.97	0.38	0.08	3.65	0.96
Photochemical smog, kg etene eq./unit	0.026	0.125	0.050	0.043	0.008	0.700	0.785

End of Table 3

Environmental impact categories	Variants floors			Variants roofs		Variants windows	
	timber	**ceramic**	**reinforced concrete**	**ceramic roof tiles**	**sheet metal roof tiles**	**wood-aluminum window joinery**	**PVC window joinery**
Toxicity to human – water, kg tox./unit	0.006	0.170	0.317	0.001	0.089	2,717	3,568
Eco-toxicity, m^3/unit	475	12,938	691	5,354	13	40	26
Eutrophisation, kg PO_4 eq./unit	0.034	0.199	0.073	0.066	0.008	0.348	0.328
Mineral use, kg/unit	132	615	552	76	2	0	110
Water, l/unit	818	892	1,185	396	335	11,804	10,595
Waste, t/unit	0.243	1.183	1.055	0.148	0.008	13,560	13,560
Transport, t·km/unit	5,597	17,772	14,051	4,280	0.921	53,754	45,385
Cost (WLC) of 1 m^2 component, [PLN]	1,173	1,413	1,184	481	335	2,154	1,608

Table 4. Values of environmental impact vectors in the whole life cycle of buildings

Environmental impact categories	Building			
	P-Basic	**C-Ceramic**	**G-Cellurar concrete blocks**	**D-Timber**
Greenhouse effect, kg CO_2 eq./ 100 year	670118	720043	699088	647739
Reduction of the ozone layer, kg CFC11 q.	2726	2726	2726	2726
Acidification, kg SO_2 eq.	47,763,631	47,763,793	47,763,629	47,763,622
Toxicity to human – airborne, kg toks.	3780	3872	3766	3759
Photochemical smog, kg etene eq.	1329	1372	1328	1319
Primary energy, MJ	14,806,648	15,289,610	14,859,911	14,766,717
Toxicity to human – water, kg tox.	28598	28661	28648	28613
Eco-toxicity, m^3	128490	134041	127486	127382
Eutrophisation, kg PO_4 eq.	12,695,557	12,695,626	12,695,553	12,695,549
Mineral use, kg	493790	611951	550061	452762
Water, l	89,367,386	89,391,219	89,410,933	89,452,309
Waste, t	65,217,161	65,217,391	65,217,257	65,217,092
Transport, t·km	80,216,676	80,219,919	80,217,718	80,215,698
Cost (WLC), PLN	1,393,000	1,427,000	1,346,000	1,329,000

- the work of people is considered as environment-friendly (no harm to the environment);
- while analysing the utilisation phase of the building, the emission from a dual-function gas boiler (heating and tap water) was assumed: energy loss for heating, based on the seasonal heat demand, and for heating tap water of 5387.04 kWh (19393.344 MJ) was calculated with KOLEKTOREK software, electric energy consumption 6000 kWh per annum. The energy loss for heating was established based on the calculations of seasonal demand for heat with a detailed method (PN-B-02025 – Calculating seasonal heat demand for heating residential buildings);
- in the wall operation phase, for the entire life cycle, the heat loss resulting from the penetration of heat flux through a partition was considered, taking into consideration the efficiency of the gas boiler;
- the following repair works were included in the 60-year operation period assumed for the house: replacement of the insulation courses in case of double-leaf walls – once, facade painting – 6 times; painting walls and ceilings – 12 times, exchange of the external sheathing and thermal insulation in the wall partition of the timber structure – once, replacement of window joinery – twice; environmental impact related to the transport of the waste to the waste dump is already covered;
- during the demolition phase, the environmental impact of transport of 20 tons is included, as required to transport the waste to the waste dump, similarly to the transport of building materials from the factory to the construction site.

In the studies carried out, impact categories were covered mostly based on the assessment of the product life cycle (Gorzynski 2002; Gorzynski and Piasecki 2002; Piasecki 2003). There are 14 such categories including the cost. Tables 2 and 3 present the calculated values of the environmental impact vectors in the whole life cycle of the variants of individual components of the building, and Table 4 gives the values for the entire building. The results presented in Table 5 illustrate the per cent share of the environmental impacts in individual phases of the life cycle of the basic variant.

Based on the analysis of the results obtained, the following conclusions can be drawn:

- the cellular concrete partition, in the basic version, has the best eco-properties regarding environment acidification, toxicity of airborne substances to human, eco-toxicity, eutrophisation and water consumption, and good properties as regards: smog, utilisation of primary energy, consumption of materials, wastes and transport;
- the utilisation of ceramic material in the walls results in the worst influence on the environment, as compared to other material solutions tested;
- a three-leaf partition made of cellular concrete exhibits the worst influence on the environment as compared to other types of partitions, as regards the reduction of ozone layer and toxicity of substances contained in water to human;
- the solution based on timber has less effect on the environment in the following categories: the greenhouse effect, impact on the ozone layer, photochemical smog, utilisation of primary energy, utilisation of minerals, transport and waster, yet it uses more water;
- the construction cost is the lowest for three-leaf cellular concrete walls.

According to the analysis of the environmental impacts due to the floors:

- the least harmful solution of a floor partition is the timber floor; such solution exhibits a negative balance as regards the greenhouse effect; the use of timber reduces the environmental influence of other products in this category,
- the floor made of ceramic material has the worst influence on the environment, except for the toxicity of substances contained in water to human and water consumption,
- reinforced concrete floor is more than the others harmful to the environment, as regards: toxicity of substances contained in water to human and water consumption.

The analysis of roofing materials indicates greater environmental impact of the ceramic roof tiles than that of the lightweight sheet metal roofing, moreover the cost of such roof is around 50% higher.

According to the comparison of the environmental impact vectors of windows, the impacts are similar for the PVC and wood-aluminium joinery, where the arguments that speak for the wood-aluminium window refer to the categories: greenhouse effect and primary energy, whereas for the PVC windows: toxicity to human – air, eco-toxicity, water consumption and transport; the cost of a PVC window is around 50% below that made of wood.

The values of the environmental impact vectors of the entire buildings throughout their life cycles are given in Table 4 together with graphic presentation. Environmental impacts differ along the individual phases of the building life cycle. The greatest impacts have been found during the phases of building use and the production of materials. In the other phases, the impacts are considerably less significant in almost all categories (see Table 5).

Table 5. Per cent share of the environmental impacts in individual phases of the life cycle

Environmental impact categories	Based variant of building				
	production	transport	build	operation	waste transport
Greenhouse effect	6.16	0.46	1.53	**91.39**	0.46
Reduction of the ozone layer	**98.15**	0	0	1.85	0
Acidification	**99.96**	0	0	0.04	0
Toxicity to human – airborne	6.26	0.88	1.97	**90.00**	0.88
Photochemical smog	4.09	0.36	3.32	**91.88**	0.36
Primary energy	0.74	0.22	0.45	**98.37**	0.22
Toxicity to human – water	**99.25**	0	0	0.75	0
Eco-toxicity,	8.75	0	3.19	**88.06**	0
Eutrophisation	**100.00**	0	0	0	0
Mineral use	11.41	0	2.40	**86.19**	0
Water	**50.21**	0	1.71	**48.08**	0
Waste	**99.96**	0	0	0.04	0
Transport	**100.00**	0	0	0	0

100% values in the table result from rounding to two decimal places; trace amounts occur in other phases.

By analysing the data provided in table 4, the following conclusions can be drawn:

- the building of the ceramic material has the strongest effect on the environment considerably in most categories, except for the influence on the ozone layer and water consumption;
- the timber building is the most efficient technical solution, except for the categories: water consumption,
- the building in its basic variant exhibits the best environmental properties in the following categories: toxicity of substances contained in water to human and water consumption, and good properties as regards: the greenhouse effect, acidification of the environment, primary energy consumption, utilisation of minerals, waste and transport; and worse as regards reduction of ozone, photochemical smog, toxicity of airborne substances, eco-toxicity, eutrophisation,
- building of cellular concrete exhibits good environmental effects in the categories: environment acidification, toxicity of airborne substances to human, photochemical smog, eco-toxicity and eutrophisation; and worse properties as regards: the greenhouse effect, ozone reduction, primary energy consumption, toxicity of substances contained in water to human, utilisation of minerals, water consumption, waste and transport,
- the lowest construction cost is involved in the timber building and slightly higher cost results for cellular concrete solutions; higher construction cost is involved while using the YTONG and ceramic components, which results mainly from the prices of wall materials.

4.2. Multi-criteria optimisation

The choice of the best solution, having the least impact on the environment is possible with the multi-criteria optimisation, or – more appropriately – the multi-criteria analysis. In the example presented as the optimisation criteria such environmental impact categories (factors) are adopted that involve the cumulated energy consumption of the building, environmental pollution and costs. These are: greenhouse effect, acidification, toxicity to human – airborne, primary energy, eco-toxicity, eutrophisation, mineral use, water, cost of 1 m^2 (or total per building) [PLN] (Table 6).

With the above criteria a separate optimisation of material solution variants was performed for individual components of the building (walls, structural floors, roofing material, window joinery) and for four versions of buildings that are made of the mentioned materials as well.

The Baas – Kwakernaak method was utilised for the optimisation, which is based on the method of weighted criteria and is shown in (Baas and Kwakernak 1977 and Nikiel 2004). In this method it is assumed that weightings and values of criteria are fuzzy numbers.

The method adopted involves the selection of an optimum solution from a finite set of acceptable solutions A (variants) $A = \{ A_1, A_2, ..., A_k, ..., A_N\}$; $k = 1, 2, ..., N$ with the set of criteria $K(A) = \{ K_i(A)\}$; $i = 1, 2, ..., M$.

Due to the deterministic character of the assessments of optimisation criteria and their different units (results of the authors' research – see Table 3, 4 and 5), for the next calculation criteria estimates were changed to point estimates (1–9 scale). Finally, the estimation of individual criteria was adopted as fuzzy numbers.

After having determined the set of feasible solutions, criteria and point scales to the assessment of solutions (alternatives) and significance of the criteria by experts (Table 6), Saaty matrices for all experts were created and, for each of them, coordinates of own vectors were created, respectively to the greatest own values. Further, the coordinates of own vectors were normalised for the matrices of criteria weighting, and coordinates characteristic for the plots of function of belonging were set. Finally, the summarised Z_r assessment for a material solution (variant) was derived from the dependency:

$$Z_r = \sum_{i=1}^{M} (W_{rozm_i} \cdot K_i(A)) \rightarrow MAX; \qquad I = 1, ..., M, \tag{3}$$

where: W_{rozm_i}, K_i – assessments of the weighting and value of an i^{th} criterion.

Table 7 presents the results of the multi-criteria analysis of the studied single-family houses and building components of various material and structural solutions, taking into consideration selected optimisation criteria, their values and significance. The calculations were executed by means program PoliOpt (Nikiel 2004).

Table 6. The point estimate of criteria weighting

Criteria	Experts estimate			Criteria	Experts estimate		
	E1	E2	E3		E1	E2	E3
K1 – greenhouse effect	9	8	8	K6 – eutrophisation	2	2	3
K2 – acidification	3	3	4	K7 – mineral use	4	4	3
K3 – toxicity to human – airborne	6	6	5	K8 – water	6	4	5
K4 – primary energy	7	5	6	K9 – cost (Whole-Life Cost)	9	8	9
K5 – eco-toxicity	6	6	5				

Table 7. The final assessment list of solutions

Building	Estimate	Wall	Estimate	Floor	Estimate	Roof	Estimate	Windows	Estimate
P	1.397	P	2.169	timber	2.120	ceramic roof tiles	1.000	PCV	1.210
C	1.000	C	1.000	ceramic	1.000				
G	1.389	G	1.989	reinforced concrete	1.639	sheet metal tiles	1.801	wood-aluminium	1.000
D	1.593	D	1.900						

4.3. Analysing the results

By analysing the results obtained from poly-optimisation, according to the criteria studied, the following conclusions can be drawn:

1) buildings:

- building solutions using timber (D) appear to be most beneficial. The timber building is least harmful to the environment, as results directly from the studies, and has an attractive price;
- the lowest grade received the building in which ceramic components prevail (C); this involves more expensive solutions – the lowest grades to all criteria;
- buildings and building components of cellular concrete are assessed relatively well, both in the basic version (P)(YTONG) and with the three-leaf walls (G);

2) walls:

- walls of YTONG (P) cellular concrete blocks received the highest grades, for environmental impacts; Ytong walls (single-leaf) received a better grade as compared to the three-leaf cellular concrete walls (G), despite higher cost;
- two-leaf walls of ceramic (C) components are the least favourable solution;

3) structural floors:

- similarly to other timber components, the timber floor, again, received the best grade;
- ceramic floor received worse grade than reinforced concrete floor, it is more expensive and less environmentally-friendly;

4) roof covering of roof ceramic tiles is more expensive and – as other ceramic components – has greater impact on the environment, which results in a lower grade (1.000), as compared to lightweight covering of pantile sheathing (2.1936);

5) PVC windows were graded higher than the wood-aluminium windows, as regards the criteria considered, they are much cheaper and less toxic to human and cause less acidification to the environment throughout the life cycle.

5. Summary

The studies carried, we succeeded in identifying the differences as to the environmental impacts of various materials and structures made of such materials and designed buildings. Such impacts are measured with a variety of factors (in the LCA method grouped in so-called vectors – thirteen vectors in the example). It is, hence, feasible to undertake the optimisation of a building design in terms of minimising such impacts, taking into consideration numerous criteria, i.e. to perform a multi-criteria analysis and to select the least harmful building.

However, the studies indicate that, bearing in mind the building life cycle, the greatest environmental impact in most categories is present during the period of building use (Table 7), due to the need for heating in winter in our climate and in most EU countries. Therefore, the development of energy-saving and environmentally-friendly building technologies is supported by the EU directives and relevant regulations.

Promotion of the assessment of environmental impacts in the entire life cycle, poly-optimisation methods and comprehensive product information, will allow the design and selection of such solutions which are both environment-friendly and least costly. It is essential to provide the designers of energy-saving and passive buildings with expert DSS systems to enhance the variant-based design process and optimisation balance (including e.g. computer-aided systems for simulative modelling of energy flow in a building).

References

Baas, S. and Kwakernaak, H. 1977. Rating and raking of multiple-aspects alternatives using fuzzy sets, *Automatica* 13: 47. doi:10.1016/0005-1098(77)90008-5.

Brandt, D. 2005. *The Passive House Know-how for Sustainable Housing*. Innovation in Building Engineering. Press. UZG.

CDP. 1989. Council Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products (89/106/EEC) (OJ L 40, 11.2.1989, p. 12).

EPBD. 2003. Directive 2002/91/EC of the European Parliament of the Council of 16 December 2002 on the energy performance of buildings, *Official Journal of the European Communities* 4. 1. 2003, L 1/65.

European Environment Agency. 1997. Life Cycle Assessment (LCA): A guide to Approaches, Experience and Information Sources, Environmental Issues Series, 6, European Environment Agency.

Giergiczny, Z. 2008. Sustainable development and production of cement, in *Sustainable in Building Industry*. Editors Lapko, A.; Broniewicz, M.; Prusiel, J. A. Press Technical University in Bialystok, 105–123 (in Polish).

Ginevičius, R.; Podvezko, V.; Raslanas, S. 2008. Evaluating the alternative solutions of wall insulation by multicriteria methods, *Journal of Civil Engineering and Management* 14(4): 217–226. doi:10.3846/1392-3730.2008.14.20.

Gorzynski, J. and Piasecki, M. 2002. Environmental declaration of products and services, *Fuels and Energy Management* 9: 6–16.

Gorzynski, J. 2002. Life Cycle Assessment (LCA) methodology of environmental analysis of products, *Fuels and Energy Management* 9: 17–25.

ISO 14040, 14041, 14042, Environmental management – Life cycle assessment.

Jaselskis, E. J. and Russell, J. S. 1992. Risk analysis approach to selection of contractor evaluation method, *Journal of Construction Engineering and Management* – ASCE 118(4): 814–821. doi:10.1061/(ASCE)0733-9364(1992)118:4(814),

Jaskowski, P.; Sobotka, A. 2004. Scheduling construction projects with resources accessibility limited and changeable in time, *Journal of Civil Engineering and Management* 10(4): 267–276.

Nikiel, G. 2004. *Multicriteria Optimisation in Production Processes Design – Chosen Problems. Report from researches*. Technical-Humanistic University, Bielsko-Biala. Available from Internet: <www.ath.bielsko.pl/~gnikiel/public/optym/pdf> (in Polish).

Norris, G. A. and Marshall, H. E. 1995. *Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems*. Building and Fire Research Laboratory National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.

Odeen, K.; Erlandsson, M.; Mingarini, K.; Nilver, K.; Sundberg, K. 1996. The application of life cycle assessment on a building component – a comparison between three different external walls and possible improvements, in *Proceedings International CIB Tg8 Workshop "Building and the Environment in Central and Eastern Europe"*, Warsaw Oct. 1996.

Piasecki, M. 2003. Energetic and ecologic characteristics external three-layered wall of building, in *Proc. of Scientific-technical Conference – Scientific-research Problems of Construction Industry*, Olsztyn-Kortowo (in Polish).

Polish Standards of Construction Works Cost Estimating 2005. Press Society of Polish Cost Estimators, Warsaw (in Polish).

Sarosiek, W. and Sadowska, B. 2006. Standard, low-energy or passive house? *International Seminar Energodom 2006, Technical Journal*, Press Technical University in Krakow, 523–530 (in Polish).

Seo, S. and Hwang, Y. 2001. Estimation of CO_2 emission in life cycle of residential buildings, *Journal of Construction Engineering and Management* – ASCE 147(8/9): 414–418. doi:10.1061/(ASCE)0733-9364(2001)127:5(414).

Shevchenko, G.; Ustinovichius, L.; Andruškevičius, A. 2008. Multi-attribute analysis of investments risk alternatives in construction, *Technological and Economic Development of Economy* 14(3): 428–443. doi:10.3846/1392-8619.2008.14.428-443.

Saaty, T. L. 1988. *Multicriteria Decision Making: Analytic Hierarchy Process*. University of Pittsburgh, Pennsylvania.

Stachniewicz, R. 2006. The comparative analysis of school object in northern-east Poland with taking energy and ecological parameters into consideration, *Technical Journal, Construction Industry*, Press Technical University in Krakow International Seminar Energodom 2006, B (5): 573–580 (in Polish).

Stephan, D. and Wilhelm, P. 2006. Innovative materials Rusing titanium dioxide – self-cleaning and photocatalyticaly active building material surfaces, *Cement International* 4(6): 2–10.

Szczechowiak, E. 2008. Changes in the building industry in terms of sustainable development, in *Sustainable in Building Industry*. Editors Lapko, A.; Broniewicz, M.; Prusiel, J. A. Press Technical University in Bialystok, 315–344 (in Polish).

Turskis, Z. 2008. Multi-attribute contractors ranking method by applying ordering of feasible alternatives of solutions in terms of preferability technique, *Technological and Economic Development of Economy* 14(2): 224–239. doi:10.3846/1392-8619.2008.14.224-239.

Turskis, Z.; Zavadskas, E. K.; Peldschus, F. 2009. Multi-criteria optimization system for decision making in construction design and management, *Inzinerine Ekonomika – Engineering Economics* 1(61): 7–17.

The Handbook of Sustainable Building. James& James Science Publisher, 1996.

Trzaskalik, T. 2008. *Introduction to Operational Research with Computer*. PWE, Warsaw [in polish].

Zagorskas, J. and Turskis, Z. 2006. Multi-attribute model for estimation of retail centres influence on the city structure. Kaunas city case study, *Technological and Economic Development of Economy* 12(4): 347–352.

Zavadskas, E. K.; Kaklauskas, A.; Peldschus, F.; Turskis, Z. 2007. Multi-attribute assessment of road design solutions by using the COPRAS Method, *The Baltic Journal of Road and Bridge Engineering* 2(4): 195–203.

Zavadskas, E. K. and Vilutienė, T. 2006. A multiple criteria evaluation of multi-family apartment block's maintenance contractors: I–Model for maintenance contractor evaluation and the determination of its selection criteria, *Building and Environment* 41(5): 621–632. doi:10.1016/j.buildenv.2005.02.019.

Zavadskas, E. K.; Kaklauskas, A.; Turskis, Z.; Tamošaitienė, J. 2008. Selection of the effective dwelling house walls by applying attributes values determined at intervals, *Journal of Civil Engineering and Management* 14(2): 85–93. doi:10.3846/1392-3730.2008.14.3.

PASTATO GYVAVIMO CIKLO DAUGIAKRITERINĖ ANALIZĖ EKOENERGETINIU POŽIŪRIU

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Santrauka

Pastaraisiais metais pasaulyje vis daugiau dėmesio skiriama aplinkosaugai ir darnaus vystymosi principų įgyvendinimui (politikos formavimui, standartų, direktyvų kūrimui ir įgyvendinimui). Lenkijoje taip pat bandoma įgyvendinti šiuos principus. Tačiau iki šiol stigo tipinių sprendimų, kuriuos investuotojas ar projektuotojas galėtų pritaikyti nekenksmingų aplinkai medžiagų, technologijų ir inžinerinių sistemų pasirinkimui, t. y. suprojektuoti pastatą, darantį mažiausiai žalos aplinkai, tuo pat metu sunaudojantį mažai energijos per visą savo gyvavimo ciklą. Pagal aplinkosaugos koncepciją pastatas turi būti suprojektuotas atsižvelgiant į visą jo gyvavimo ciklą, o jo konstrukcija ir inžinerinės sistemos turėtų užtikrinti minimalų poreikį šildyti eksploatuojamą pastatą. Straipsnyje pateikiama daugiakriterinė pastato variantų analizė atsižvelgiant į jo gyvavimo ciklą. Metodas įvertina rodikliais apibūdinamas poveikio aplinkai kategorijas, paskui priimamas sprendimas, užtikrinantis mažiausią poveikį aplinkai. Atliekant daugiakriterinę analizę ir priimant optimalų sprendimą vertinami svarbiausieji poveikiai ir kaina. Ekoenerginio pastato variantų vertinimo rezultatai yra pagrindas sprendimams priimti projektuojant ir eksploatuojant pastatus, taip pat vertinant kitus aspektus (eksploatacinius, socialinius).

Reikšminiai žodžiai: darnusis vystymasis, gyvavimo ciklo įvertinimo metodas, daugiakriterinė analizė, optimizavimas, projektavimo paramos metodas.

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