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Nalysis of green solutions for new residential projects

Analiza rozwiązań ekologicznych dla nowych inwestycji mieszkaniowych

Abstract
Improvement of the ecological aspect in residential buildings is connected with the need for high investment expenses, which meets with little interest from investors, who are mainly interested in decreasing investment building costs rather than maintenance costs or environmental protection. To change this attitude, it is necessary to evaluate the validity of applications in terms of pro-ecological solutions, technologies and materials used. This is the basis for developing a mathematical decision support model when choosing ecological solutions. Application is demonstrated on the example of the selection of ecological solutions for a residential building.

Keywords: decision making, ecological criteria, ecological evaluation of a building, decision optimization

Streszczenie
Poprawa ekologiczności budynków mieszkalnych wiąże się z koniecznością poniesienia wysokich nakładów inwestycyjnych, co spotyka się z niewielkim zainteresowaniem ze strony inwestorów, których interesuje przede wszystkim obniżenie kosztów inwestycyjnych budowy, a nie kosztów eksploatacyjnych i ochrona środowiska. Aby zmienić to nastawienie, konieczna jest ocena zasadności stosowania proekologicznych rozwiązań projektowych, technologicznych i materiałowych. Problem stanowił podstawę do opracowania matematycznego modelu wspomagania decyzji przy doborze rozwiązań ekologicznych. Jego zastosowanie pokazano na przykładzie jednorodzinnego budynku mieszkalnego.

Słowa kluczowe: podejmowanie decyzji, kryteria ekologiczne, ocena ekologiczna budynku, optymalizacja wyboru

1. Introduction

Housing development based on outdated project solutions, energy-inefficient materials and fossil fuels largely contributes to a detrimental effect on the natural environment. It is responsible for high energy and water consumption as well as the changes in the quality of air and atmosphere [1, 2]. The reduction in the amount of natural resources consumed by the construction industry is a key factor for the environment. In order to limit its negative influence, it is necessary to simultaneously apply modern technology, materials, designs, and introduce changes in the behaviour and consumption models of building users. This means that apart from the introduction of innovative technologies and solutions to the market, it is necessary to take actions facilitating the awareness of their use and try to broaden the knowledge of investors and users as to the available possibilities of shaping the influence of buildings on the environment, both during actual use and at the investment planning stage.

Ecological housing combines the issues of the rational design, efficient execution, economical structure exploitation, ecology, and optimum conditions of use [7]. To fulfil these conditions it is necessary to use modern material and execution technologies, renewable energy sources (solar panels, geothermal, wind energy, heat pumps), and a responsible composition of the architecture into the surrounding environment etc. In order to achieve these goals, it is necessary to reach proper cooperation among designers, investors, the construction industry, and the contractors. This cooperation covers the following aspects: construction resource design and management, material selection, practical properties of the building, as well as the contribution to urban and economic growth [9].

New apartments offered on the market only meet ecological requirements to a small extent. This is the result of a number of factors, such as social, economic, cultural, and behavioural, which influence investors' decisions in various degrees. Nevertheless, it is currently visible that environment-related issues tend to be increasingly noticed by investors, as they determine how attractive an apartment or a house is on the market. More attention is currently paid to the application of design, material and technological solutions.

This interest has become the subject of scientific research, in which authors present the profitability of applying solutions improving the sustainability of buildings. Unfortunately, while assessing the solutions for the construction industry the dominant factor determining their choice is energy saving in the building without taking into consideration other important factors that determine the building's sustainability [8]. It can be assumed that this attitude will be changed together with the increase of ecological awareness of future accommodation customers whose requirements will become higher with time and they will concern more advanced solutions leading to the improvement in the sustainability of buildings. Currently, many of the pro-ecological solutions offered on the market, particularly related to the renewable energy sources based systems, are reluctantly used in the contemporary housing industry. The cause may be found in the fact that improving the sustainability of a building is connected with higher investment costs, which undoubtedly limits the implementation of pro-ecological solutions in the housing industry.

It is a difficult task to convince an investor to apply ecological solutions, since, apart from the environment-related arguments, it also requires a demonstration of other benefits such as economic and social. There is a need, therefore, to develop tools which would serve for the evaluation and comparison of materials, technologies and processes in respect of a balanced development involving environmental, economic and social benefits [6, 7, 9]. The challenge that the authors undertook was to create a decision support model with the consideration of ecologically efficient solutions. The model demonstrated in the paper constitutes a multi-stage approach, which includes both the selection of the evaluation criteria and ecological solutions as well as an evaluation of given ecological solutions in order to point out those which lead to the biggest benefits complying with the construction cost minimization.

2. Sustainable development in construction

The concept of balanced development in housing is connected with creating and responsible management of the urban area based on the rule of effective and ecological use of natural resources. It takes into consideration environmental factors, the quality of life, cultural issues, social justice, and economic limitations [9]. It is necessary to underline the fact that such an approach may differ depending on the type of a building undertaking (housing, office, industrial and infrastructural structures etc.).

Activities undertaken for the purpose of balanced housing objectives can be divided into pro-ecological (environmental), economic, and social [1, 7]. The pro-ecological (environmental) actions are intended to minimize the negative influence on the natural environment, mostly through efficient use of natural resources, recycling, waste production limiting and the use of renewable energy sources. The economic actions are related to lowering the economic costs (reduction of material and energy consumption) throughout all the lifespan stages of a building. The social actions are to improve the quality of life mostly through improving the interior environment quality, the transportation solutions and through appropriate localization of a building.

The way to accomplish the objectives of balanced housing is based on the proper application of scientifically prepared methods which allow an evaluation to be made and the material, technology, structural solutions, construction process, variants and strategies in respect to meeting the requirements of the balanced development in the best possible way to be selected. In practice, it relies on a multi-criteria decision support system during the design, realization, exploitation and demolition stages.

3. Housing investment preparation

The most important stage of the investment process is the preparation stage, during which the decisions affecting the whole lifespan of a building are made. The decisions made at this stage have to result from the analyses of many criteria, the building's influence on people and the environment during the states of construction, exploitation and demolition. What is crucial during the preparation stage is the selection of the concept and the methods used to accomplish the task. This requires strict cooperation among all of the participants involved in the design process. The primary concept and project assumptions may determine the success of all the following stages of the construction process, the funding model for the structure as well as the possibility to reuse the resources and demolish the building in a way that enables further recycling of materials.

The preparation of the project documentation should comply with the multi-criteria optimization of the decision making with the consideration of the needs of investors (investment cost minimization), users (exploitation cost minimization) and the environment (detrimental effect minimization). The factors that must be considered in the design of an ecological building are as follows [3, 7]:

- Energy saving,
- The use of renewable energy sources,
- The possibility of material recycling,
- The improvement of the quality of the interior environment (acoustics, ventilation, heating),
- Saving natural resources (terrain, water, air),
- Building localization and geographical orientation,
- Lifespan prolongation of a building,
- Improvement in transportation solutions.

In order to adopt specific project solutions (architectural, installation) it is necessary to meet a number of requirements related to urban planning, utility supply methods, guarantees of construction and fire safety, providing essential health and hygiene conditions, environment and landscape preservation as well as protection against noise and tremors.

4. The description of the proposed method

The proposed decision-making support method for the preparation of an ecological design for a housing project is supposed to help make the optimal choice of solutions improving the sustainability of a building. It involves four stages, which require doing proper calculations (the solution evaluation and selection optimization) as well as choosing ecological solutions for a building and the evaluation criteria for them. Individual stages of the prepared model are shown in Figure 1.

The evaluation of a building's sustainability is a significant element during the stage of building concept development. In order for the building to meet the ecological requirements, it is necessary to select and properly define its evaluation criteria K_j. When selecting them, we must take into consideration the economic, environmental and social aspects as well as clearly define the effects of its influence on the environment and the tenants. The stage of selecting the ecological solutions for the analysis will reflect the subjective and individual approach of a person who prepares it. The selection of a proper ecological solution set R

= $(r_1, r_2, \ldots, r_n)$ requires appropriate market research in terms of the solutions improving the sustainability of buildings on offer. When choosing the ecological solutions, it is, first of all, important to consider the technical possibilities of applying them in a building (the shape of a building, its location, surroundings, etc.). The prepared set of i th solutions should make it possible to improve the sustainability of a building in respect of the assumed evaluation criteria.

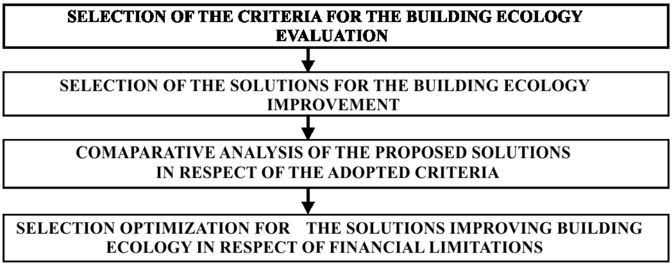

Fig. 1. The stages of the proposed method

The proposed ecological solutions for building need an evaluation concerning the adopted criteria. For that purpose the fuzzy AHP method was adopted [4, 5], which makes it possible to aggregate the opinions of a number of experts. Each of them makes $m = n(n-1)/2$ pairwise criteria comparisons using the following grading scale: 1, 3, 5, 7, 9 possibly extended with intermediary marks. As a result of the pairwise criteria comparisons a matrix set $A_k = \{a_{ijk}\}, i = 1,2,\ldots,n-1,\ j = 2,3,\ldots,n,\ j > i,\ k = 1,2,\ldots,K$ is obtained, where a_{ijk} denotes a preference of the criterion mark i over j, reflected in the adopted fuzzy grading scale and expressed by an expert k. The aggregated evaluation marks are obtained from the following equations [5]:

$$l_{ij} = \min(a_{ijk}), \quad m_{ij} = \left(\prod_{k=1}^{K}{}_{ijk}\right), \quad u_{ij} = \min(a_{ijk}) \qquad (1)\ (2)\ (3)$$

For the aggregated expert evaluations, the characteristic points of triangular membership functions $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ are calculated using equation [5]:

$$\tilde{r}_{ij} = \left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{1/n} \quad where: \quad \tilde{o}_{ij} = \tilde{r}_{ij} \Big/ \sum_{i=1}^{n} \tilde{r}_{ij} \quad i = 1,2,\ldots,n \quad j = 1,2,\ldots,m \quad (L_{ij}, M_{ij}, U_{ij}) \qquad (4)\ (5)$$

The fuzzy set obtained through the aggregation of the partial marks requires defuzzification in order to obtain crisp mark values for the individual solutions. The defuzzification procedure is carried out using the BNP method (Best Nonfuzzy Performance) [4]:

$$o_{ij} = \frac{L_{ij} + M_{ij} + U_{ij}}{3} \tag{6}$$

The solution marks obtained for the individual criteria are the basis for the next calculations with the use of the optimization method prepared. Its purpose is to identify the most efficient ecological solutions for the adopted improvement assumptions of the criteria evaluation marks concerning the sustainability of the building. This means that the most economical solution option which meets the assumptions s_{jz} for the criterion j is sought. The evaluation of every sustainability criterion of a building is carried out on the basis of equation (9), while the selection of the ecological solution option is made on the basis of the target (7) as a result of the optimization procedure. The mathematical description of the optimization method is presented in the following way:

$$\min z : z = K \tag{7}$$

$$K = K_b + K_r \tag{8}$$

$$s_j = \sum_{i=1}^{n} \sum_{h=1}^{t} o_{ij} \cdot x_h \quad i = 1,2,...,n, \;\; h = 1,2,...,t \tag{9}$$

$$s_j \geq s_{jz} \quad \forall \;\; j = 1,2,...,m \tag{10}$$

where:

- K – the cost of the prepared building concept [PLN/m^2],
- K_r – the ecological solutions cost [PLN/m^2],
- K_b – the base building cost[PLN/m^2],
- o_{ij} – the evaluation of the i th ecological solution for the j th criterion,
- s_j – the evaluation of the j th criterion,
- s_{jz} – the projected evaluation of the j th criterion,
- x_h – the binary variable.

5. A calculation example

The application of the decision support system in terms of ecological solutions selection is presented using the example of a single-family detached house, whose usable floor area is 250 m^2. It was assumed that the base cost of the building was K_b = 3500 [PLN/m^2]. This reflects the average price of one square metre of usable floor area for a detached house in the Lubelskie Voivodeship. For the purpose of the analysis, six criteria were adopted for the evaluation of the building's sustainability. The criteria, along with the description of their influence effects are presented in the Table 1. These criteria do not include all possible activities related to the improvement of the ecological effectiveness of the building, but only constitute a portion of those whose application requires increasing certain investment costs when compared to a building constructed only for the purpose of meeting the modern legal and norm related requirements.

Table 1. The evaluation criteria for the building sustainability and their influence effects

j	Criterion K_j	The evaluation of the ecological effects
1	Energy saving	the improvement of the building partition isolation limiting the heat loss in the building
2	The use of renewable energy sources	the use of heating, ventilation, air conditioning and electrical systems powered by renewable energy sources
3	Interior environment quality	the improvement of the practical apartment convenience in terms of acoustics, ventilation, heating, lighting
4	Material recycling	the possibility of use and reuse of processed materials or their adaptation for other purposes
5	Environment pollution	the limitation of pollution sources such as waste, exhaust fumes which are disposed in the exterior environment
6	Reasonable use of natural resources	The use of natural resources which do not require a high level of processing (low accumulated energy consumption)

Table 2 presents the ecological solutions proposed for further analysis. The set below consists of nine solutions, whose application enables the improvement of the building sustainability in terms of the criteria *k*.

Table 2. Proposed changes for the improvement of the building sustainability

i	Ecological solution r_i with description	
1	Ground heat exchanger for the central heating system	Pipe heat exchanger in a broken version with length of 50 m with inlet sampling point
2	Mechanical ventilation with recuperation	Mechanical supply and exhaust ventilation ($V = 350$ m^3) with cross flow heat exchanger
3	Solar system for domestic hot water (DHW)	System built out of two flat solar collectors with 300 litres DHW storage container
4	Photovoltaic installation	system built out of 12 photovoltaic panels with power of 3.06 KW –without batteries
5	Household sewage treatment system	Biological sewage treatment system 2.5 m^3 with infiltration area
6	Energy-efficient lighting system	Energy-efficient light source (LED technology) with automated control
7	Passive exterior carpentry	Energy-efficient carpentry $U_w = 0.6$ W/m^2·K
8	Passive exterior building partition	External double layer partition in system $U = 0.11$ W/m^2·K
9	Passive bedplate	Bedplate in lost shuttering system $U = 0.09$W/m^2·K

In order to establish the significance of the proposed solutions, 10 experts were asked for their opinions. Each of them made an evaluation through pairwise comparisons of the significance of the *i* th solutions for every *j* th criteria. Then, on the basis of (1)–(3) relations, the aggregation of the marks was performed. On the basis of the aggregated opinions $\tilde{a}_{ij}$ with the use of the equations (5) the values of the fuzzy evaluation vector $\tilde{o}_{ij} = (L_{ij}, M_{ij}, U_{ij})$ of the *i* th solutions were calculated for the *j* th criteria. As a result of the conducted calculations modified by the AHP method the crisp values of the marks of the *i* th solutions in regard to the *j* th ecological criteria were obtained. The cost of the proposed solutions was obtained through the requests for quotation. The values were shown in Table 3.

Table 3. The evaluation of the ecological solutions oij and the solution cost K_r

r_i	The evaluation of the ecological solutions for *j* th sustainability criterion						K_r [PLN/m²]
	1	2	3	4	5	6	
1	0.103	0.156	0.043	0.244	0.084	0.336	64
2	0.128	0.085	0.178	0.043	0.09	0.036	48
3	0.086	0.153	0.054	0.047	0.073	0.039	12*
4	0.086	0.159	0.054	0.053	0.072	0.041	32*
5	0.046	0.266	0.042	0.132	0.204	0.172	52
6	0.085	0.079	0.109	0.046	0.058	0.051	28
7	0.146	0.036	0.158	0.095	0.129	0.084	140
8	0.189	0.033	0.19	0.161	0.187	0.127	72
9	0.13	0.033	0.171	0.179	0.103	0.114	144

* The price includes financial support

The final calculation stage for the proposed model was to identify the optimal set of ecological solutions. For the calculations, the assumptions s_{jz} which are related to the improvement of the building sustainability in terms of the *j* th criteria were adopted. As a result of these optimization calculations, the most satisfactory solutions for the improvement of the building sustainability were identified. The results are shown in Table 4.

Table 4. Selected ecological solutions ri for the adopted assumptions s_{jz}

The assumed mark s_{jz}/received mark s_j for the *j* th criterion						Selected ecological solutions r_i	Solution variant cost K_r [PLN/m²]
1	2	3	4	5	6		
0.3/0.402	0.3/0.473	0.3/0.384	0.3/0.380	0.3/0.305	0.3/0.462	1, 2, 3, 6	152
0.5/0.592	0.5/0.586	0.5/0.519	0.5/0.548	0.5/0.506	0.5/0.579	1, 2, 3, 4, 8	228
0.7/0.783	0.7/0.808	0.7/0.774	0.7/0.768	0.7/0.825	0.7/0.845	1, 2, 3, 5, 6, 7, 8	416

6. Conclusion

The analysis of the ecological solutions dedicated to a single-family detached house presented in the paper involves merely a narrow range of the applicable solutions offered by manufacturers. Improvements in housing sustainability require taking a number of actions leading to measurable effects in the environmental, economic and social aspects. It is possible to achieve them mostly thanks to the application of modern solutions for the improvement of building sustainability. This is connected, however, with the need to increase the investment costs in comparison to the conventional building solutions, which effectively limits their use.

The perception of building sustainability in terms of higher investment costs without noticing the effects which it is possible to achieve requires certain changes in approach from the investor. The decision support system concerning the selection of sustainability improvement solutions may serve as an example. It constitutes an innovative tool which may be helpful at the stage of the building concept formulation. It takes into account the construction cost limitations searching for the cheapest solutions leading to the desired improvement in the building sustainability. The mathematical methods used for the calculation of the individual model tasks facilitate its application in the practice.

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